

Final Report

Benthic Habitat Maps of San Francisco Bay Interpreted from Multibeam Bathymetric Images and Side-scan Sonar Mosaics

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Executive Summary

San Francisco Bay's sub-tidal habitats support a variety of fishes and invertebrates and constitute nursery grounds for several commercially important species. These habitats are currently at risk, however, due to a variety of stressors including increased coastal development, mining, and expansion of marine transportation systems. In an effort to better manage and restore sub-tidal habitats in the Bay, the National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service (NOS) and National Marine Fisheries Service (NMFS) have developed a multidisciplinary collaborative project. The overall project goals are to collect and analyze data from existing and newly conducted geophysical surveys to determine the quantity and quality of sub-tidal habitats. Habitat and species information will be compiled and decision support/analysis tools will be developed to enhance coastal management of estuarine habitats such as eelgrass beds, rock reefs, sand shoals, oyster reefs, and tidal channels.

As part of this collaborative effort, NOS contracted the Center for Habitat Studies (CHS) of Moss Landing Marine Laboratories (MLML) to construct estuarine benthic habitat maps from existing and newly collected marine geophysical data sets and to conduct sediment analyses (see Appendix I). This project began in August 2002 and was funded for a term of one year. Map interpretation and processing have been completed and 9 separate digital habitat maps have been constructed.

Approximately 120 km² of archived multibeam data and 50 km² of side-scan sonar data, collected in the fall of 2002, were interpreted for habitat characterization. Ninety-one distinct estuarine benthic habitat types were identified and Bay-floor samples, collected by the USGS and NOS, were used to document substrate type and groundtruth habitat interpretations. The defined habitats typically range between 10 and 30 m of water depth and deepen to approximately 50 m at the northern extent of the survey area. The sedimentological history of the region extends back to approximately 10 Ma with the initiation of a major sediment depot center in a graben between the Hayward-Calaveras and San Andreas Fault zones. Modern sedimentation from fluvial input and tidal scouring has resulted in a dynamic and complex Bay-floor. Strong currents have produced large sediment wave fields, rippled sediment patches, and scoured channel floors and walls. Soft habitats composed primarily of mud and/or sand dominate the region while hard rocky and mixed habitats are relatively rare and occur mainly in shallow areas adjacent to peninsulas and islands. Anthropogenic effects such as debris fields and dredging are distinctly displayed in the data and delineated on the habitat maps.

Among geophysical data sets, the side-scan sonar data provided the best textural information while the multibeam bathymetry provided the best Bay-floor relief information and imaged the dynamic bedforms and scoured features especially well. In our estimation, the best approach to image the San Francisco Bay-floor is with the use of a high-resolution multibeam system (i.e., Reson 8111 or 8101 sea-floor mapping system) outfitted with the appropriate acquisition and processing software for the collection of high-quality backscatter data. In addition, a high-resolution sub-bottom seismic reflection profiling system could add a necessary dimension by imaging sediment thickness. However, if funding is limited, side-scan sonar surveys are probably the best cost-effective way of collecting data for benthic habitat mapping. Bathymetric information will be sacrificed if this technique is used, but resultant imagery is amenable to confident habitat interpretations. It should be noted that, with either technique, considerable variables play a role in cost including vessel size and expense, weather conditions (can lead to down time or poor quality data), and type of instrument used, to mention a few.

Introduction

San Francisco Bay is the largest estuary along the California coast. It is a Type B (well-mixed) estuary resulting from saltwater and freshwater mixing by strong tidal currents and continuous, periodically intense river flow. Much of the freshwater contribution to the Bay is from the interior drainage basin of the Great Central Valley of California and fed by the San Joaquin and Sacramento rivers. The strong tidal currents scour and erode, as well as transport sediment along the Bay-floor. Although little coarse-grain fluvial sediment is presently being supplied to the Bay, extensive coarse-grain deposits exist as relict sediment, which are the result of hydraulic gold mining in the late 1800s. In our study area, west-central San Francisco Bay and Carquinez Strait, several islands (i.e. Angel Island, Alcatraz Island) and bedrock mounds rise above the Bay-floor and may be the source of locally derived sediment.

The lower San Francisco Bay area lies within a graben that forms the depot center for sediment accumulation. The graben is a tectonic feature that has formed from transtension associated with differential movement along the active San Andreas and Hayward-Calaveras fault zones, which essentially bound the western and eastern side of the graben. This tectonic activity has occurred since approximately 10 Ma, resulting in a thick (kms) accumulation of sediment that formed a significant sedimentary basin. Basement rock is derived from the Jurassic-Cretaceous Franciscan Complex and crops out on prominent mainland points, islands, and locally on the Bay-floor. Granitic rocks crop out on the San Francisco Peninsula west of the San Andreas Fault. Unconformably overlying the basement rocks are Tertiary sedimentary rocks comprised primarily of marine sedimentary deposits of sandstones, siltstones, mudstones, and conglomerates. Locally derived modern sediment is supplied to the Bay region through erosion of basement rock, bedrock, and unconsolidated alluvial deposits exposed around the periphery of the Bay and on the Bay-floor. However, this contribution is insignificant due to the now limited outcrops and the artificial sediment impediments in place on streams and creeks that drain into the Bay. This is a high-density urban area with little natural drainage paths in existence. The largest sediment supply to the Bay comes from the Sacramento River and this contribution is primarily of fine-grain sediment as much of the pathways for coarse-grain sediment have been anthropologically disrupted. Some coarse-grain sediment in the form of coarse sand, gravels, pebbles, and cobbles exist in the Bay, but these are primarily relic deposits that have been reworked by the present-day current regime.

The dynamic geology of the San Francisco Bay region has resulted in the creation of several estuarine habitats (i.e., eelgrass beds, rock reefs, sand shoals, oyster reefs, and tidal channels) that support a variety of fishes and invertebrates and constitute nursery grounds for several commercially important species. These habitats, however, are currently at risk due to a variety of stressors including increased coastal development, mining, and expansion of marine transportation systems. As part of this multidisciplinary collaborative effort to better manage and restore sub-tidal habitats in the Bay, NOS contracted the Center for Habitat Studies (CHS) of Moss Landing Marine Laboratories (MLML) to construct estuarine benthic habitat maps from existing and newly collected marine geophysical data sets and to conduct sediment analyses in order to groundtruth habitat interpretations (see Appendix I). The utility of the geophysical data sets and of side-scan and multibeam survey techniques as a basis for habitat interpretations was evaluated and recommendations were made for future work.

Objectives

The primary objective of this project was to utilize previously collected multibeam bathymetric and side-scan sonar data from west-central San Francisco Bay and Carquinez Strait to produce digital estuarine benthic habitat maps. Specific contractual obligations included: 1) interpretation of Bay-floor imagery into habitat types using a marine benthic habitat characterization code developed at the CHS of MLML and modified from Greene et al. (1999), 2) groundtruthing of habitat interpretations, facilitated through grain-size analysis of previously collected Bay-floor sediment and augmented with additional sediment grab samples, 3) construction of a GIS in ArcView® comprised of digital imagery and habitat themes, and 4) completion of a final report and appropriate project metadata, and 5) an evaluation of the utility of the provided side-scan and multibeam data and of each general collection technique for habitat mapping. All project objectives have been met.

Data Sources

Sea-floor imagery for this project consisted of four side-scan (Figure 1) and five multibeam mosaics (Figure 2) recently collected in west-central San Francisco Bay and Carquinez Strait. Side-scan surveys were conducted in west-central San Francisco Bay in 2002 by NOAA's Office of Coast Survey and covered an area of approximately 50 km². Resulting side-scan .tif files provided to the CHS and used during habitat interpretations were termed: Region A, Region B, Region C, and Region E. No file for Region D was provided. Multibeam surveys, covering an area of approximately 120 km², were conducted in 1997 by C&C, Inc. (under USGS contract) in the region surrounding Angel Island and in 1999 and 2000 by David Evans and Associates (under NOAA contract) in west-central San Francisco Bay and Carquinez Strait. Resulting multibeam .tif files provided to the CHS and interpreted into habitat types were termed: USGS, h10896, h10960, h10961, and h10962. All imagery used in this project was processed prior to the onset of this project and could not, therefore, be modified.

Methods

The multibeam bathymetric and side-scan sonar data sets were interpreted into habitat types using a deep-water marine benthic habitat scheme modified after Greene et al. (1999). This process requires several steps, which can be separated into five main categories: 1) data processing and creation of layouts, 2) interpreting the sea-floor imagery (contained in each layout) into habitat types, 3) processing the habitat interpretations, 4) groundtruthing habitat interpretations with sediment samples, and 5) creating a final GIS project. The methods used in each of these steps are detailed below.

Using the side-scan or multibeam imagery provided by NOS, layouts were created in ArcView® and exported as .tif files using the extension ArcPress. This process was repeated at different scales (in multiples of 500) for each region until a final scale was chosen for habitat interpretations. The final scale was determined from a combination of factors including: the scale at which sea-floor features were most distinct without pixelation of the imagery (data quality), the area of each region, the financial and temporal limitations of the contract award, and the desire to maintain consistency in mapping scales between regions, whenever possible. Side-scan sonar data from Region A, B, and E were interpreted at a scale of 1:5,000 while data from Region C were interpreted at 1:3,000. Data

for Region C were interpreted at a higher resolution due to the reduced area of that region (2.8 km²) as compared to the others (47.2 km², combined). Multibeam data for area h10961 and offshore Angel Island were interpreted at 1:6,500, areas h10986 and h10962 at 1:5,000, and h10960 at 1:10,000. Differences in interpretive scales for multibeam data were largely a function of differences in data quality and area between regions.

Once final mapping scales were established for each region, layouts were plotted at 36" x 30" and used as a basis for habitat interpretations. Mylar sheets were affixed over the final printed layouts and coordinate tic marks were copied onto the Mylar sheets for later georeferencing. For this project, all files were projected in Universal Transverse Mercator (UTM) Zone 10 with a NAD 83 datum and spheroid.

A coding system was established to distinguish marine benthic habitat types for demersal species of interest and to facilitate ease of use and queries in GIS and other database programs. This code was modified from the deep-water habitat characterization scheme developed by Greene et al. (1999) and is based on interpretations of sea-floor geology, morphology, and biology. A copy of this habitat attribute code and a corresponding explanation are included in this volume (see Classification Scheme and Classification Scheme Explanation, see Appendix II) and can be found on the MLML Center For Habitat Studies web site: www.mlml.calstate.edu/groups/geooce/habcent.htm. At the request of NOS, the question-mark symbol (?), typically used to denote probable or questionable habitat attributes, was replaced with an asterisk (*). These designations applied only to bottom induration attributes.

Dr. H. Gary Greene and Dr. Tracy Vallier interpreted Bay-floor imagery into habitat types as the first step in map production. This was done on a light table by drawing polygons around distinct habitat features based on knowledge of the geology of the study region. Multibeam bathymetric and side-scan sonar data provided a general picture of where bedrock and unconsolidated sediment were located with lithologic contacts being interpretive. Although Bay-floor imagery overlapped in places, habitat interpretations based on this imagery were not merged due to temporal differences in data collection and the dynamic nature of the San Francisco Bay substrate and benthos, which resulted in very little consistency between overlapping regions.

Mylar interpretations, consisting of 16 individual sheets among the nine survey regions, were scanned, georeferenced to 0.5m, and processed in GIS programs (TNT Mips® and ArcView®). Scanned mylars were then printed and the habitats depicted were attributed and color-coded. This procedure also served as a double-check to edit the habitat interpretation as needed. Processed files (rasters) were edited in the Spatial Data Editor within TNT Mips®. Unwanted features such as speckles, attribute numbers and text from the polygons, and tick marks are erased during this process. Dashed lines were connected and missing lines were re-drawn using a drawing tool. The scanned, printed and colored mylars were used as reference for editing. The final raster file was then converted to a vector file using the Auto Trace method in TNT Mips®. Several tests were run before the final conversion to check the results of the line editing and tracing.

The vector file was then edited to delete or add nodes and lines and to correct the shape of polygons. During vector editing, the original side-scan and multibeam geotiffs were used for reference. Original geotiffs were imported into TNT Mips® using the correct georeferencing and then projected as layers underneath the vector file in the Spatial Data Editor.

The edited vector was then warped to create an implied georeferenced with the output projection set as specified above. Smoothing of the warped vector file was performed with the Vector Filtering tool based on necessity. If the lines were too angular, smoothing was used to better round the curves. Several tests were run before the final smoothing to make sure no features were omitted during processing.

This process was repeated for each file and warped and filtered vector files derived from the same study region were then merged, resulting in the reduction in 9 final vector files (one for each survey region) from 16 original vector files. Final cleaning was done in the Spatial Data Editor. Again, the original multibeam and side-scan sonar geotiffs were projected as layers underneath the vector file and used for reference. Special attention was paid to the overlying areas to ensure that all the lines meet and polygons were closed and accurately depicted. Once final cleaning changes were made, each file was exported as a shapefile (.shp).

Shapefiles were opened in ArcView® where a legend file was added and the following attribute fields were included: Hab_code, Hab_type, Mega_ID, Mega, Ind_ID, Ind, Mes_Mac_ID, Mes_Mac, Mod_ID, and Mod. Each file was checked for proper georeferencing and for overlapping polygons. Shapefiles consisting of georeferenced sediment samples collected by the USGS in 1985 and NOS in 2003 (analyzed for grain size) were overlaid on the habitat shapefiles in ArcView®. A layout comprising each habitat map and overlying sediment information was prepared and printed at 36" x 30" in order to groundtruth habitat interpretations. Habitat attributes were modified based on sediment samples resulting in the final project shapefiles. Habitat shapefiles were then copied and copies were edited to eliminate all modifiers for bottom induration, at the request of NOS. This resulted in two sets of final digital habitat maps, each consisting of nine shapefiles. Area analysis was performed on the original shapefiles using the Feature Geometry Calculator extension in ArcView® (Note: Area calculations are based on data projected in UTM Zone 10, NAD 83. It may be desirable to perform area analysis on unprojected data, if a high-degree of accuracy is required for statistical calculations or planning purposes). The original shapefiles were incorporated into an ArcView® project (.apr) along with the imagery from which they were interpreted, to create a final project GIS.

Habitat Interpretations

Ninety-one estuarine benthic habitat types were defined from the supplied geophysical data sets using a marine benthic habitat characterization scheme modified after Greene et al. (1999) that was adapted to estuary conditions (Table 1). These habitats ranged from hard bedrock outcrops on the island and mainland flanks and Bay-floor to soft, dynamic bedforms consisting of sediment waves and ripples. Soft sediment was the dominant induration type (90.9%, by area) and ranged from mud and sand to bimodal (two or more grain sizes) sediment of gravel, pebbles, and cobbles. Mixed (6.5%) and hard (2.6%) habitat types were relatively rare (Table 2). In addition, approximately 16% of the identified hard substrate consisted of anthropogenic features (i.e., pipelines, bridge abutments, dredged channels, dump spoils) with the remainder consisting of rock outcrop. Confidence of interpretation ranged from well defined or known (based on sediment samples or known rock type in outcrop) to inferred (an intelligent guess) to questionably inferred (uncertain without further information). The inferred and questionable aspects of the interpretation are represented in the habitat codes with an asterisk.

Geophysical Data Sets

Merging distinct, overlapping data sets for habitat interpretations was not possible due to the temporal differences in data collection and the variations in data type and quality. Due to the strong current regime, the San Francisco Bay-floor is a dynamic, sedimentary environment with major bedforms that are inclined to shift in position and shape. Over time, significant alteration of the Bay-floor takes place and substrate types may shift or disappear entirely. This type of activity precludes the combining of data collected at different times into a single substrate or benthic habitat map.

The geophysical data sets used for this project overlap in several areas. Imagery for Region E (side-scan) and h10960 (multibeam) and Region B and h10962 overlap extensively. However, the multibeam imagery was of much lower interpretive quality. This disparity and the three-year difference between surveys precluded merging the datasets, although some common elements (esp. dredge channels, anthropogenic features) were observed. The USGS (Angel Island) multibeam imagery overlaps with other regions of both side-scan (Regions A and B) and multibeam (h10961 and h10962). These data sets were also interpreted distinctly, however, due to similar differences in the temporal nature of data collection, the differences in data quality, and the general lack of consistently observed features between data set. Consequently, we provide a series of maps, or themes, in a GIS that represent interpretations of each of the nine geophysical data sets described previously. Each should be treated distinctly and represents the best possible interpretation given the quality of the imagery used and the substrate conditions at the time of survey.

NOAA Side-Scan Sonar Data

Side-scan sonar data collected by NOAA in the summer of 2002 were provided to the CHS for interpretation. These data were collected using a Klein 3000 dual frequency (nominal 100 and 500 kHz) sea-floor mapping system in four different locations: 1) Region A, near the mouth of the Bay, 2) Region B, east of Angel Island, 3) Region C, east of Treasure Island, and 4) Region E, in the northern part of the south Bay. These data were generally of high quality and facilitated interpretation of the textural characteristics of the area. Strong nadir stripping reduced the aesthetic quality of the data somewhat, but interpretation of reasonable confidence could be made regardless of this interference (Figure 3).

NOAA Multibeam Data

Four disparate sets of multibeam bathymetry (h10960, h10961, h10962, h10896), collected by NOAA in 1999 and 2000, were provided to the CHS for habitat interpretations. These data sets were collected in 1999-2000. No backscatter information was included and the data were gridded at 2 m and color coded by depth. Although resolution was poor and no grayscale images or grids were available, we were able to confidently interpret Bay-floor habitats and produce maps that appear to correlate well with the known geology. Higher resolution images with backscatter would, however, have resulted in more detailed interpretations (Figure 4).

USGS Multibeam Data

Simrad EM 300 (30 kHz) multibeam data collected by C&C Inc. for the USGS in 1997 was obtained from the USGS web site at a gridding of 4 m, because the highest data resolution was not available. Persistent and continuous attempts by both NOS and CHS personnel to obtain either data processed at higher resolution or raw data that could be gridded at a higher resolution were unsuccessful. We were therefore forced to interpret the data under less than optimal conditions. In addition, the associated backscatter data obtained from the web site was not of high quality and provided minimal textural information. To overcome these handicaps, we enlarged the data set as much as possible without pixelating it, produced several artificial sun-shaded relief images with sun illumination from different directions, and undertook multiple interpretations. This worked well except in areas of steep relief (i.e., margins of Bay and islands) where it was not possible to distinguish fine textures (Figure 5).

USGS and NOAA Sediment Samples

The USGS provided 56 sediment grab samples for grain size analysis (Figure 6). These samples were analyzed to USGS standards using equipment and instruments at the USGS Sedimentology Lab in Menlo Park, California. A full report of these analyses is included as Appendix I. Another 30 samples, collected by the NOS in spring 2003 in areas selected by CHS personnel, were classified into gross sediment types (mud, sand, cobble, etc.; Figure 6). Sediment samples were used to groundtruth habitat interpretations from remotely collected data sets. This information was extremely useful in documenting habitat types. However not all habitat types were groundtruthed due to the limited number of available sediment samples and the significant amount of time elapsed since the collection of USGS samples (18 years).

Results, Conclusions, and Recommendations

Although they cover only a portion of San Francisco Bay, the completed habitat maps represent the most comprehensive deep-water benthic habitat interpretation of San Francisco Bay to date. Ninety-one habitat types have been distinguished and represent a diverse variety of sea-floor conditions ranging from hard bedrock to soft dynamic sediment bedforms. Strong tidal currents within the Bay continuously alter the substrate and benthos and thus many of the interpreted habitat types represent a condition that existed during the time of data collection, but possibly not long afterwards. Others, such as bedrock outcrops along island and mainland flanks or exposed as pinnacles or mounds rising above the Bay-floor, are more permanent. Therefore, the maps presented here are time slice representations for the dates the data were collected. Some of the habitat types may be now have different morphologies then shown in the interpreted maps or may have disappeared entirely.

The data used in habitat interpretations were diverse and of varying quality. NOAA side-scan sonar data were generally of high quality and facilitated interpretation of the textural characteristics of the area. Although resolution was poor and no grayscale images or grids were available from NOAA multibeam data, we were able to confidently interpret Bay-floor habitats, though grayscale sunshaded images with backscatter would have resulted in more detailed interpretations. Although the best USGS multibeam data in the Angel Island area was not available, imagery used provided for confident and detailed habitat interpretations were better facilitated by associated backscatter

data. Sediment samples provided by the USGS and NOS were important in verifying interpreted habitat types.

Based on the availability of good high-resolution side-scan sonar and multibeam bathymetric mapping systems, better quality and higher resolution data can be collected today than even the recent past. Nevertheless, the data used for this study were invaluable in producing habitat maps for the San Francisco Bay area. The use of these data show that achieved data sets can be utilized at relatively low cost to produce comprehensive benthic habitat maps

Estuary floors are generally difficult to acoustically image because of the varying water masses and acoustic velocity structures produced from freshwater-saltwater tidal mixing. When using multibeam bathymetric mapping systems, fairly continuous CTD measurements can be obtained to regularly update the velocity numbers used in data processing. However, this is a bit more difficult to do with side-scan sonar systems and thus could lead to poorer quality data than is possible using multibeam bathymetric systems. Nevertheless, conducting surveys at optimal times (i.e., during ebb or flood tides when the water mass may be of a constant density) can reduce this problem substantially. Therefore, if leeway in timing a survey is available, side-scan survey techniques are probably the least expensive way to map benthic habitats in estuaries today. However, the expense of undertaking a marine benthic habitat survey is dependent upon a multitude of variables such as: 1) the size and cost of a vessel needed for the study, 2) whether the equipment is leased or its capital investment needs to be recovered, 3) the size of the area to be surveyed, 4) the time of year the survey is conducted (due to weather conditions that may impact ability to collect high quality data), 5) the staff or crew needed for the collection of data, and 6) the type of processing required. All of these factors, and more, play a role in the cost of a mapping project.

In regard to equipment types used to image sea- and estuary-floors, several evaluations have been undertaken to compare and contrast the various systems that are available for habitat mapping (Kenny et al. 2000, Brissette and Hughes-Clark, 1999). Although these evaluations were done several years ago, they generally hold today and we refer the reader to these articles for further information. We also include (see Appendix III) a series of tables provided in the article by Kenny et al. (2000) that compare footprint resolution, relative performance, time required to cover specific areas, time vs. resolution, and types of seabed conditions. Although this type of assessment was done for the general marine environment, it has tremendous application to estuaries. We, therefore, refer the reader to these reference tables before designing a survey.

Based on the articles by Brissette and Hughes-Clark (1999) and Kenny et al. (2000) and since the Bay-floor is relatively flat in comparison to other parts of the continental margin, we conclude that bathymetric data could be sacrificed for the acquisition of good textural information necessary for defining substrate types. In this case, we would recommend the use of a state-of-the-art high resolution (100-500 kHz) Chirp digital side-scan sonar system for future mapping efforts in the San Francisco Bay area. However, we believe that a suite of mapping tools are necessary to obtain the highest quality and most comprehensive data sets for the interpretation of habitat types in estuaries. These mapping tools would include high-resolution multibeam bathymetric and georeferenced backscatter data (i.e., Reson 8111 or 8101) collected using the most up-to-date acquisition technology and proto-snippet or snippet processing software. In addition, a high-resolution sub-bottom seismic reflection profiling system (preferably a Chirp system) should be used to determine the thickness of sedimentary units. These data can be used to determine the migratory aspects of the various soft dynamic bedform habitats. For the shallow water, tidally influenced parts of the Bay,

LiDAR and hyperspectral data is not useful due to the turbidity of the water. However, digital photographs and multibeam bathymetric or side-scan sonar data collected during times of very high tides could provide valuable data that would enable the construction of seamless habitat maps from the deep water to the shoreline.

We recommend that a general dynamic bedform habitat map be constructed for the deep-water part of the central Bay using the interpretive data collected for this study. This map would distinguish temporal and persistent habitats and address the dynamic influences that rework the Bay-floor. This type of map construction was not possible as part of the current study but would provide good supplemental information for the habitat maps produced during this project. In addition, this type of analysis (comparison of temporal habitat shifts) could provide rates of sea-floor change and distinguish areas of the most dynamic influences. Further surveys should also be undertaken to fill in the data voids as only a very limited area of the San Francisco Bay complex was mapped in this study.

Literature Cited

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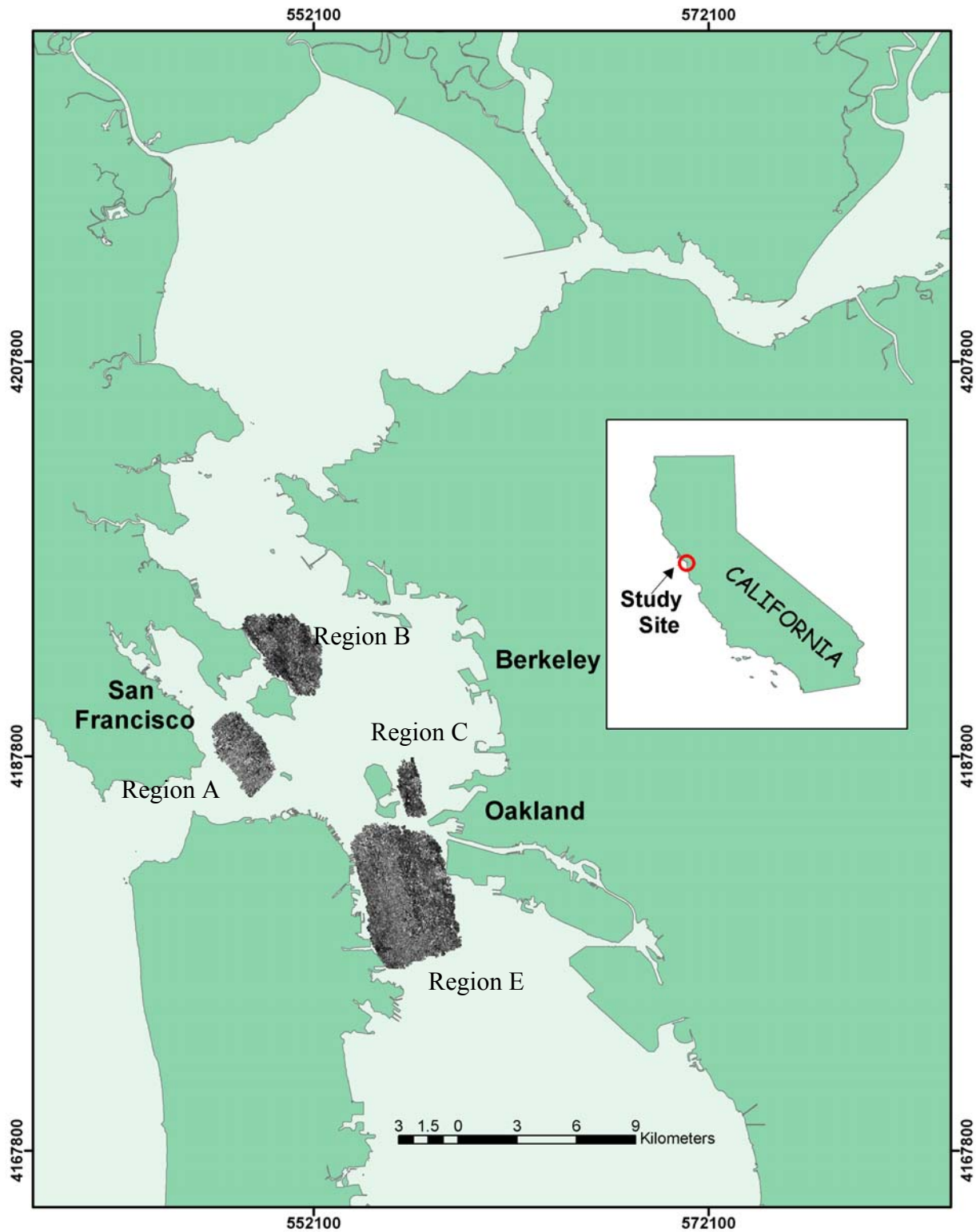


Figure 1. Side-scan sonar mosaics utilized for habitat interpretations in west-central San Francisco Bay. Surveys covered an area of approximately 50 km² and were conducted in 2002 by the National Oceanic and Atmospheric Administration's (NOAA) Office of Coast Survey.

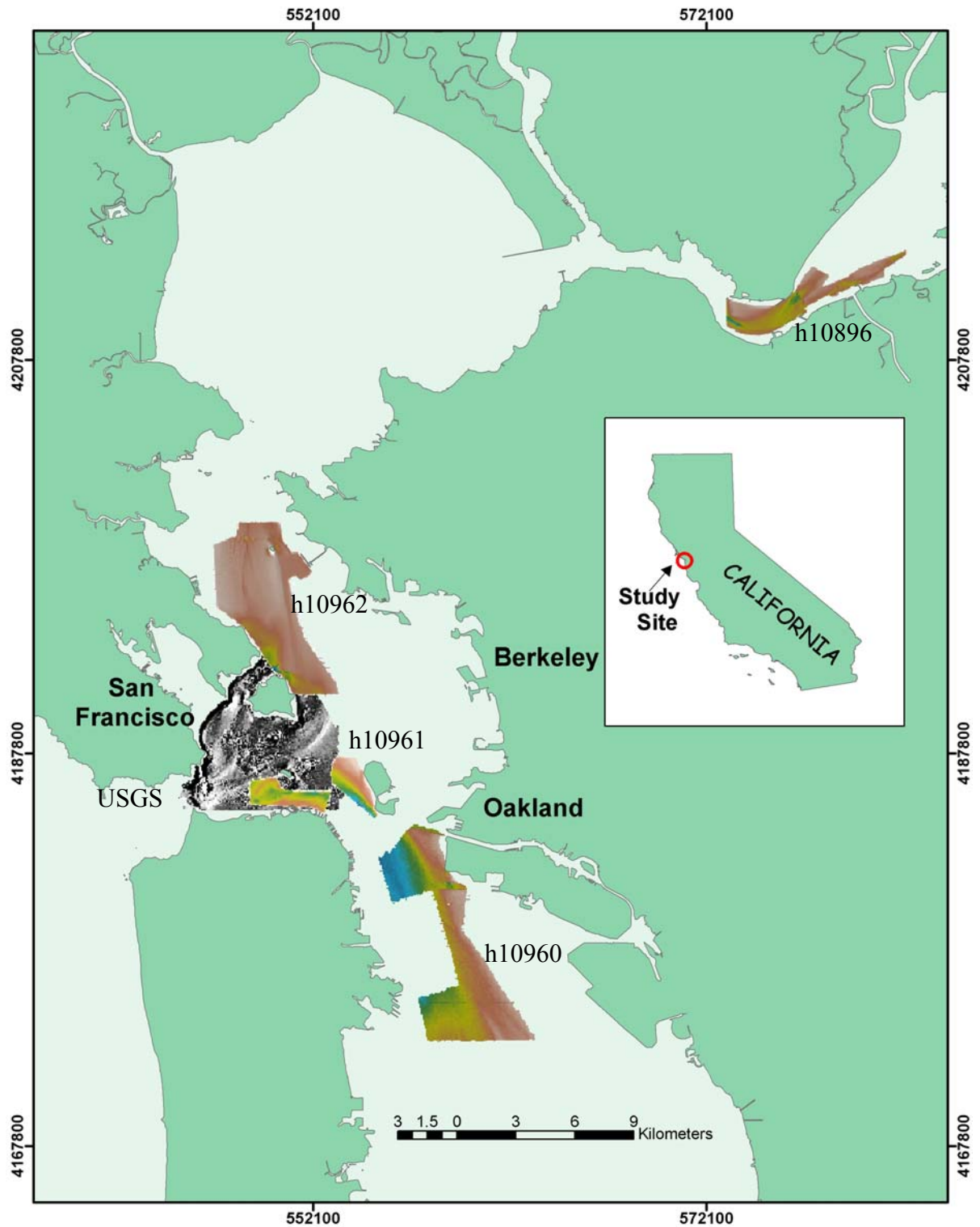


Figure 2. Multibeam mosaics utilized for habitat interpretations in west-central San Francisco Bay and Carquinez Strait. Surveys covered an area of approximately 120 km² and were conducted in 1997 by the United States Geological Survey (grayscale) and in 1999 and 2000 through a NOAA contract to David Evans and Associates (color-shaded).

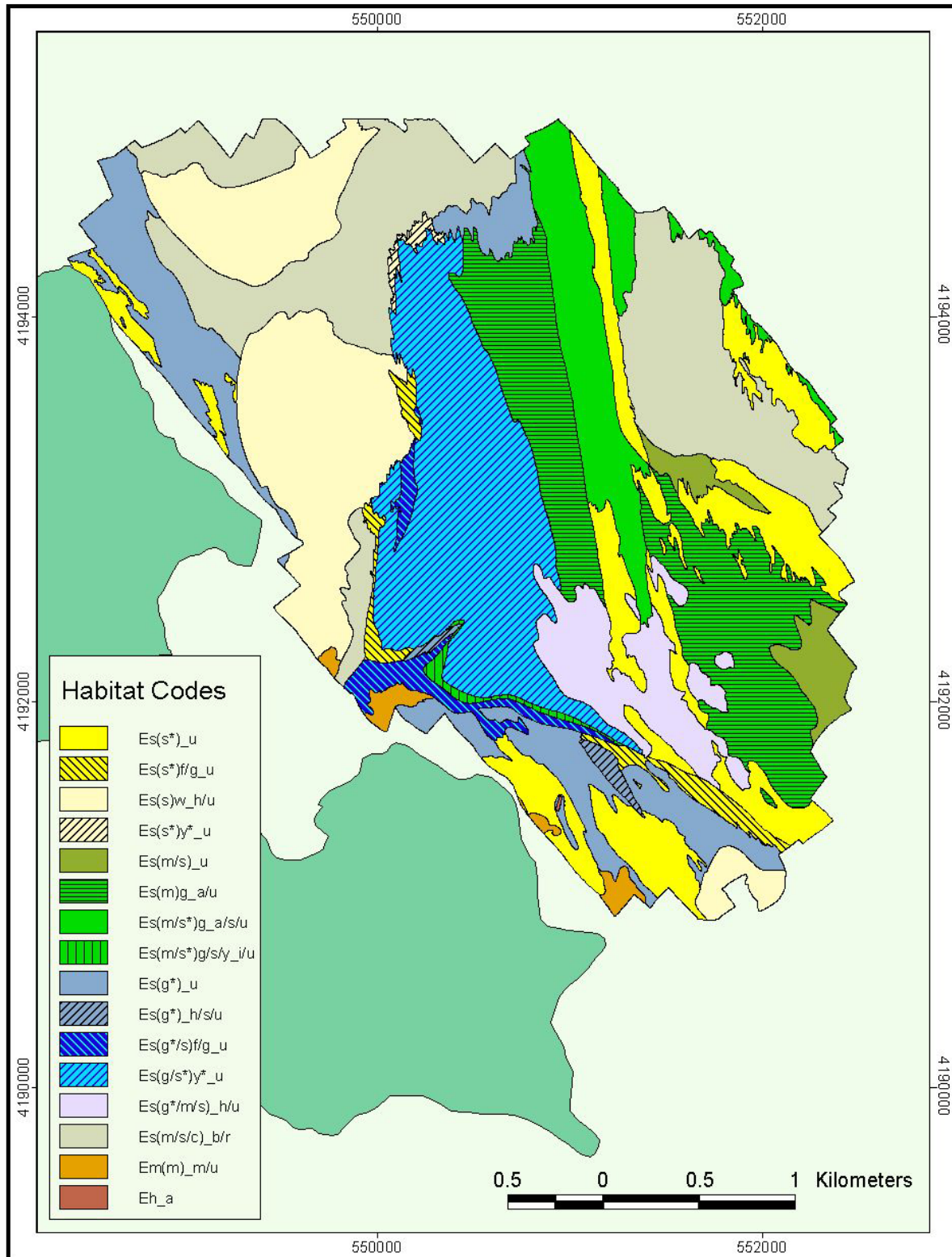


Figure 3. Habitat map interpreted from a side-scan mosaic (Region B) and groundtruthed with sediment samples. Sixteen distinct habitat types were characterized of which 1 consisted of hard, 1 of mixed, and 14 of soft substrate types.

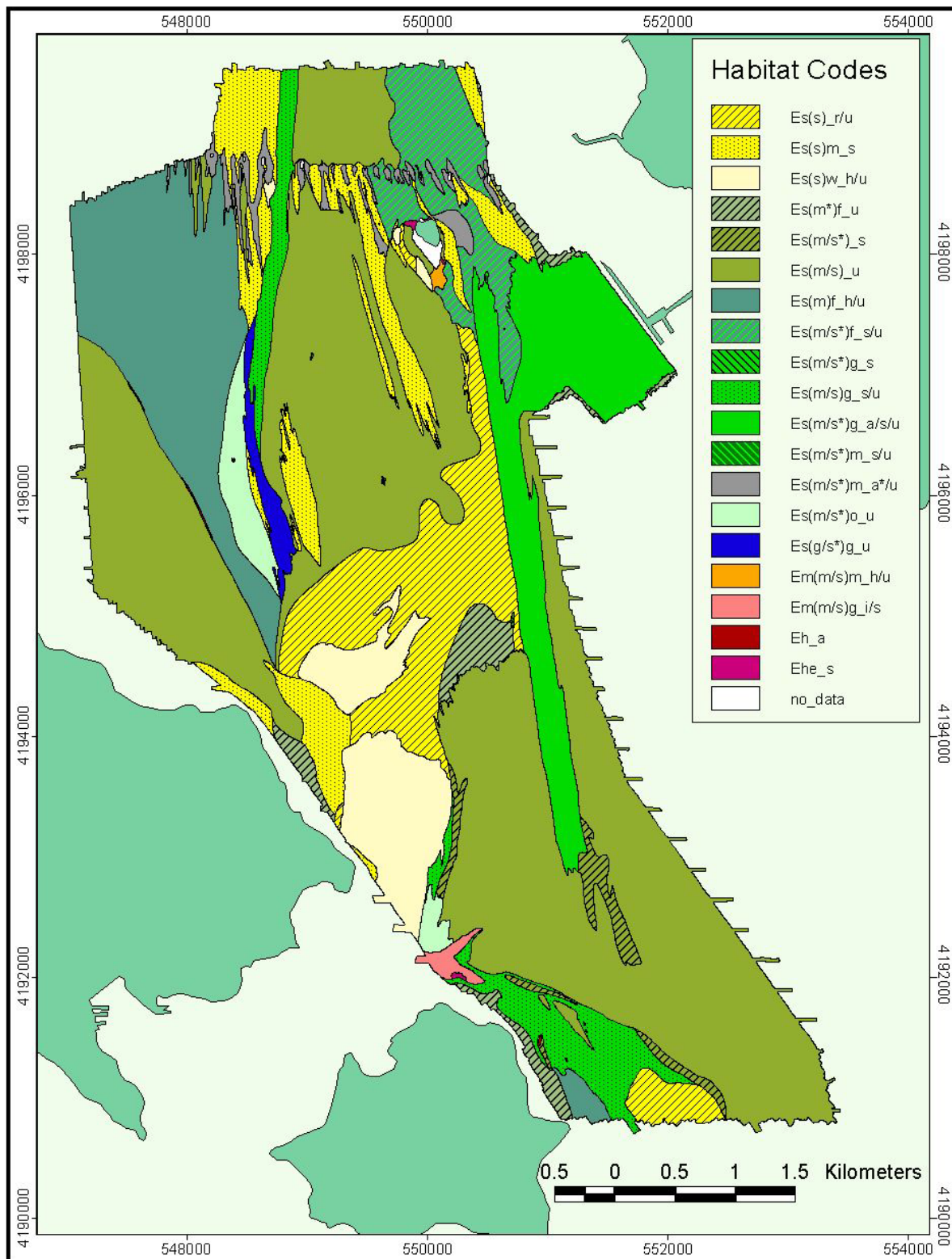


Figure 4. Habitat map interpreted from multibeam imagery (Region h10962) and groundtruthed with sediment samples. Nineteen distinct habitat types were characterized of which 2 consisted of hard, 2 of mixed, and 15 of soft substrate types.

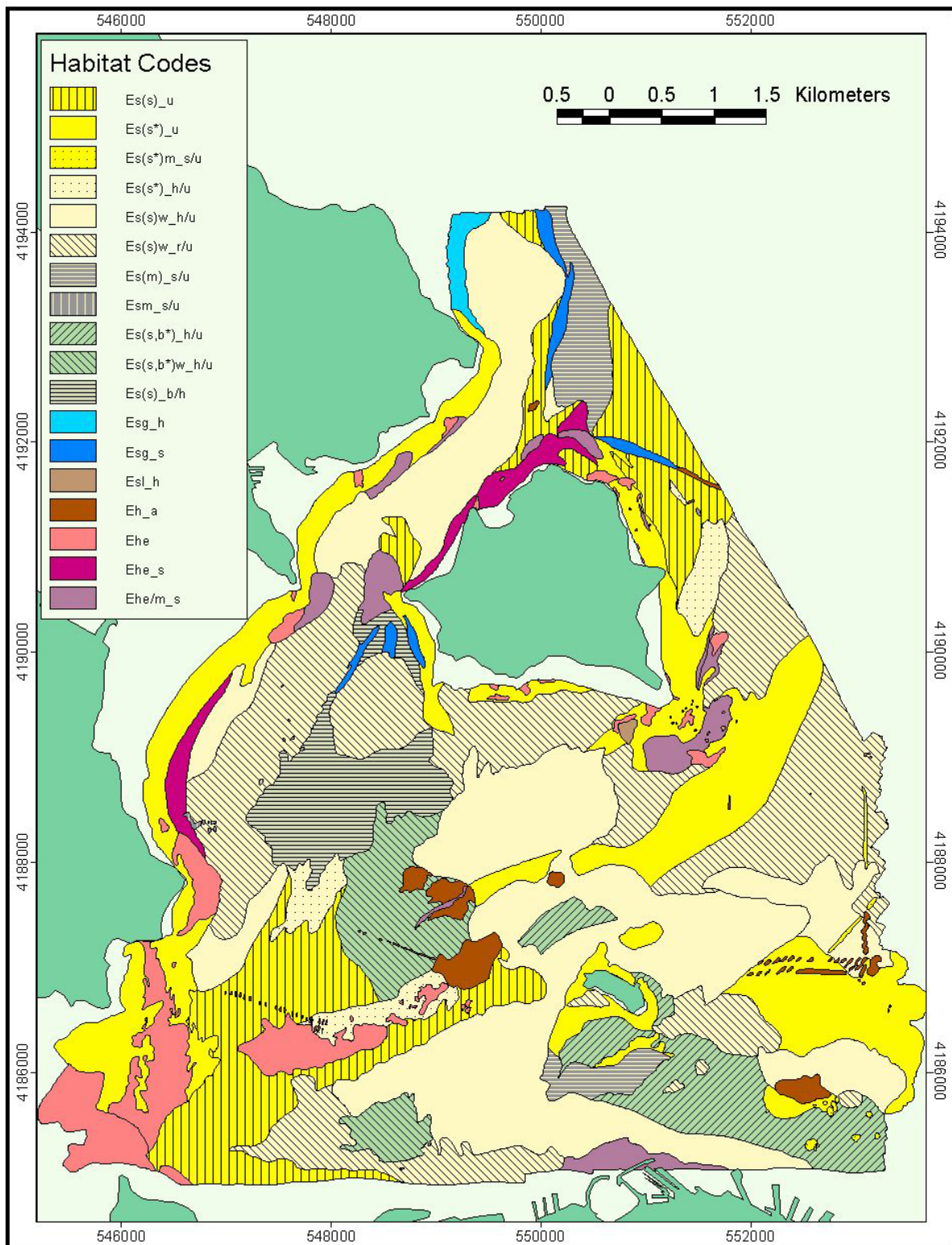


Figure 5. Habitat map interpreted from USGS multibeam imagery and groundtruthed with sediment samples. Nineteen distinct habitat types were characterized of which 4 consisted of hard and 14 of soft substrate types.

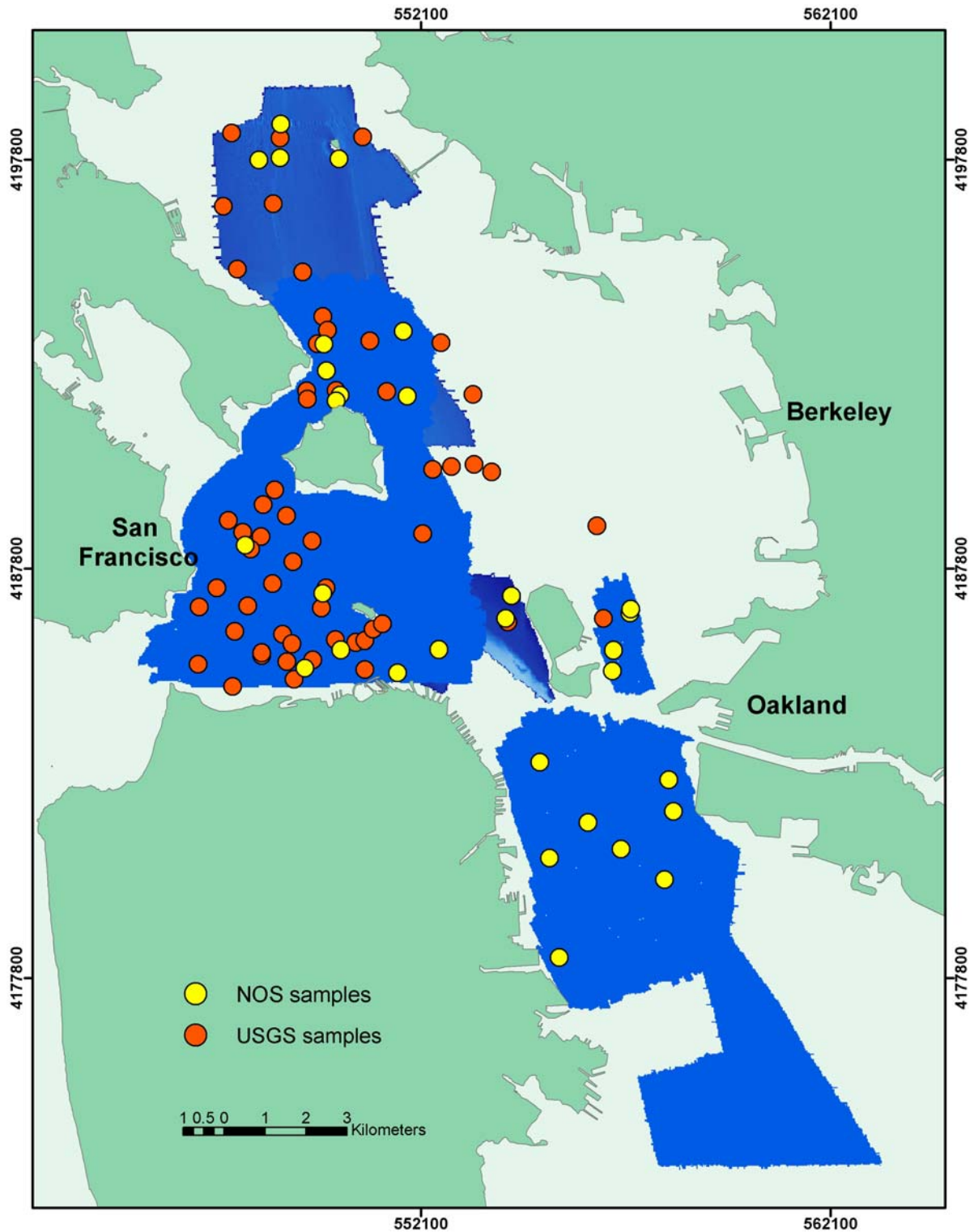


Figure 6. Locations of sediment samples collected by the United States Geological Survey (USGS; red) in 1985 and the National Ocean Service (NOS; yellow) in 2003. 56 USGS and 30 NOS samples were used to groundtruth habitat interpretations. Seafloor imagery utilized for habitat interpretations is depicted in blue.

Table 1. Key to all habitat types characterized from seafloor imagery. A total of 91 habitat types were depicted from five multibeam and four side-scan sonar mosaics. Habitats are attributed (see Habitat Codes) based on a marine benthic habitat characterization scheme modified from Greene et al. (1999). An asterisk (*) denotes attributes which are questionably inferred and, therefore, uncertain.

Habitat Code	Habitat Type
1. Es(s*)_u	Soft unconsolidated sediment (possibly sand) in estuary
2. Es(s)_u	Soft unconsolidated sediment (possibly sand) in estuary
3. Es(s)_r/u	Soft unconsolidated sediment (sand) ripples in estuary
4. Es(s*)f/g_u	Soft unconsolidated sediment (sand) on gully/channel floor, in estuary
5. Es(s*)g_s/u	Soft unconsolidated sediment (possibly sand) in scoured channels and gullies in estuary
6. Es(s)m_s	Soft scoured sediment (sand) mounds and depressions in estuary
7. Es(s*)m_s/u	Soft scoured unconsolidated sediment (possibly sand), mounds and depressions in estuary
8. Es(s*)_h/u	Soft unconsolidated hummocky sediment (possibly sand) in estuary
9. Es(s)w_h/u	Soft unconsolidated sediment (sand) with hummocky sediment waves in estuary
10. Es(s)w_r/u	Soft unconsolidated rippled sediment (sand) in estuary
11. Es(s*)y*_u	Soft unconsolidated sediment (possibly sand) on fingers and stringers, in estuary
12. Es(s*)_a/s/u	Soft unconsolidated sediment (possibly sand) dredged channels, scoured, in estuary
13. Es(m*)g_u	Soft unconsolidated sediment (possibly mud) in wide, deep channel, rare bedforms in estuary
14. Es(m)_u	Soft unconsolidated sediment (mud, silt, clay), in estuary
15. Es(m*)f_u	Soft unconsolidated sediment (possibly mud), tidal flats in estuary
16. Es(m/s)m_u	Soft unconsolidated sediment (mud, sand), mounds and depressions, in estuary
17. Es(m/s*)_s	Soft scoured sediment (mud and possibly sand) in estuary
18. Es(m/s*)_u	Soft unconsolidated sediment (mud and possibly sand), in estuary
19. Es(m/s)_u	Soft unconsolidated sediment (mud, silt, clay/sand) in estuary
20. Es(s/m)_u	Soft unconsolidated sediment (muddy sand) in estuary
21. Es(m/s*)_s/u	Soft unconsolidated sediment (mud, possibly sand), scouring with irregular bedforms in estuary
22. Es(m/s*)_h/s/u	Soft unconsolidated hummocky sediment (mud, possibly sand), some scouring in estuary
23. Es(m/s*)_a/s/u	Soft unconsolidated sediment (mud, possibly sand), scoured, dredged channels, in estuary
24. Es(m/s*)_a/h/u	Soft unconsolidated sediment (mud, possibly sand), anthropogenic, hummocky dump along dredged area in estuary
25. Es(m)_a/h/u	Soft unconsolidated sediment (mud, silt, clay), anthropogenic debris dump, hummocky, in estuary

Habitat Code	Habitat Type
26. Es(m)f_h/u	Soft unconsolidated hummocky sediment (mud, silt, clay), on tidal flats in estuary
27. Es(m/s*)f_s/u	Soft scoured unconsolidated sediment (mud, possibly sand) on tidal flats in estuary
28. Es(m/s*)g_s	Soft scoured sediment (mud, possibly sand), gullies and channels in estuary
29. Es(m/s*)f/g_s/u	Soft unconsolidated sediment (mud, possibly sand) wide channel floor, scoured in estuary
30. Es(m/s)g_s/u	Soft unconsolidated sediment (mud, silt, clay/sand) in scoured channels and gullies in estuary
31. Es(m)g_a/u	Soft scoured unconsolidated sediment (mud, silt, clay) over dredged channels in estuary
32. Es(m/s*)g_a/s/u	Soft scoured unconsolidated sediment (mud and possibly sand), dredged channels and ridges in estuary
33. Es(m*/s)g_a/s/u	Soft scoured anthropogenic unconsolidated sediment (possibly mud and sand), dredged channels in estuary
34. Es(m/s*)g/s/y_i/u	Soft unconsolidated sediment at interface between scoured gully/channel and fan-like sediment in estuary
35. Es(m)_s/u	Soft unconsolidated sediment (mud, silt, clay), scouring with irregular bedforms in estuary
36. Esm_s/u	Soft unconsolidated sediment, mounds and depressions scour with local irregular bedforms in estuary
37. Es(m/s*)m_s/u	Soft unconsolidated sediment (mud, possibly sand) mounds and depressions, scouring, in estuary
38. Es(m/s)m_a*/u	Soft unconsolidated sediment (mud, sand), mounds and depressions (pocked), anthropogenic(questionable), in estuary
39. Es(m/s*)m_a*/u	Soft unconsolidated sediment (mud, possibly sand), mounds and depressions (pocked), anthropogenic (questionable), in estuary
40. Es(m/s*)o_u	Soft unconsolidated sediment (mud, possibly sand), overbank deposits in estuary
41. Es(m*/s)w_h/u	Soft unconsolidated sediment (possibly mud and sand) with hummocky sediment waves in estuary
42. Es(s,b*)_h/u	Soft hummocky unconsolidated sediment (sand, possible boulders) in estuary
43. Es(s,b*)w_h/u	Soft unconsolidated sediment (sand, possible boulders) with hummocky sediment waves in estuary
44. Es(g*)_u	Soft unconsolidated sediment (possibly gravel) in estuary
45. Es(g*)_h/s/u	Soft unconsolidated sediment (possibly gravel), hummocky and scoured, above channel floor in estuary
46. Es(g/s*)_u	Soft unconsolidated sediment (gravel and possibly sand) in estuary
47. Es(g*/s)_u	Soft unconsolidated sediment (possibly gravel and sand) in estuary
48. Es(g/s*)_r/u	Soft unconsolidated sediment (gravel and possibly sand), ripples in estuary
49. Es(g/s*)_s/u	Soft unconsolidated sediment (gravel, possibly sand), scoured, wide unconfined channel in estuary
50. Es(g/s*)g_u	Soft unconsolidated sediment (gravel, possibly sand), channel deposits in estuary
51. Es(g/s*)g_s/u	Soft unconsolidated sediment (gravel, sand) in deep scoured channels, near debris, bridge pilings in estuary
52. Es(g*/s)g_s/u	Soft unconsolidated sediment (possibly gravel, sand) in deep scoured channels, near debris, bridge pilings in estuary
53. Es(g*/s)f/g_u	Soft unconsolidated sediment (possibly gravel, sand) on gully/channel floor, in estuary

Habitat Code	Habitat Type
54. Es(g*/s)w_h/u	Soft unconsolidated hummocky sediment (possibly gravel, sand), sediment waves, in estuary
55. Es(g/s*)y*_u	Soft unconsolidated sediment (gravel, possibly sand) on a surface with fan-like morphology, in estuary
56. Es(g/s*)y_h/u	Soft unconsolidated hummocky sediment (gravel, possibly sand), apron/fan down-current from channel, in estuary
57. Es(g/s*)_a/s/u	Soft unconsolidated sediment (gravel, possibly sand) scoured, dredged channels in estuary
58. Es(g/s*)_a/h/u	Soft unconsolidated hummocky sediment (gravel, sand) anthropogenic debris, current modified, in estuary
59. Es(m/g*/s*)_u	Soft unconsolidated sediment (mud, silt, clay possibly with gravel/sand), in estuary
60. Es(g*/m/s)_h/u	Soft unconsolidated hummocky sediment (gravel, mud, sand) with irregular mounds in estuary
61. Es(g/m/s*)_a/h/u	Soft unconsolidated sediment (gravel, mud, possibly sand), anthropogenic, hummocky debris dump in estuary
62. Es(c/g/s*)_a/h/u	Soft unconsolidated hummocky sediment (cobbles, gravel, possibly sand), anthropogenic debris dump, in estuary
63. Es(c/g/s*)_a/h/s/u	Soft unconsolidated sediment (cobbles, gravel, possibly sand), some scouring, hummocky debris dump in estuary
64. Es(c/g/s)_r/u	Soft unconsolidated sediment (cobble, gravel and sand), ripples in estuary
65. Es(c/g/s*)s_a/h/u	Soft unconsolidated hummocky sediment (cobbles, gravel, possibly sand), along dredged channel in estuary
66. Es(b/c/s)m_a/h	Hummocky sediment, mounds, depressions with anthropogenic debris in estuary
67. Es(b/c*)_a/h/s/u	Soft unconsolidated sediment (boulders, possibly cobbles), some scouring, reworked debris dump in estuary
68. Es(m/s/c)_b/r	Soft unconsolidated rippled sediment (mud, silt, clay/sand/cobbles) in estuary
69. Es(s)_b/h	Soft unconsolidated bimodal, hummocky sediment (sand) in estuary
70. Es(s)_b/r	Soft unconsolidated bimodal, rippled sediment (sand) in estuary
71. Es(g/p/s)m_h/s	Soft unconsolidated, hummocky, current scoured sediment with mounds & depressions in estuary
72. Esg_s	Soft scoured sediment in a gully, in estuary
73. Esg_h	Soft hummocky sediment on channel wall in estuary
74. Esl_h	Soft hummocky landslide deposit in estuary
75. Em_d/u	Differentially eroded bedrock mixed with unconsolidated sediment in estuary
76. Em(m)_m/u	Mixed hard and soft bottom (clay/mud), massive bedrock with unconsolidated sediment, in estuary
77. Em(m/s*)_m/u	Mixed hard massive bedrock and soft unconsolidated sediment (mud, possibly sand) in estuary
78. Em(g/s*)_m/u	Mixed hard massive bedrock and unconsolidated sediment (gravel, possibly sand) in estuary
79. Em(g*/m/s*)_d/h/u	Mixed hummocky sediment (possibly gravel, mud, possibly sand) differentially eroded, with covering pockets of unconsolidated sediment, in estuary
80. Em(m/s)m_h/u	Mixed rock/hummocky soft sediment (mud, silt, clay/sand), mounds and depressions in estuary

Habitat Code	Habitat Type
81. Em(s*)m_s/u	Mixed hard/soft bottom, mounds/depressions, scouring, massive bedrock covered by sand(questionable) in estuary
82. Em(s)e_m	Exposed massive bedrock mixed with unconsolidated sediment (sand) in estuary
83. Em(m)e_m	Exposed massive bedrock mixed with unconsolidated sediment (clay/mud) in estuary
84. Em(m/s)g_i/s	Mixed (mud, silt, clay/sand), channel scoured into bedrock, sediment walls(questionable), in estuary
85. Em*(g/s*)g_d/s/u	Mixed (questionable) hard and soft sediment (gravel, possibly sand) differentially eroded, deep scours, eroded edge of terraces
86. Em(m)t_d/s/u	Mixed sediment (mud, silt, clay), terrace-like feature, differentially eroded, some scouring, in estuary
87. Eh_m	Hard bottom, massive bedrock of unknown character in estuary
88. Eh_a	Hard bridge pilings and large pieces of discarded debris in estuary
89. Ehe	Hard bedrock or firm mud outcrop in estuary
90. Ehe_s	Hard scoured bedrock or firm mud outcrop in estuary
91. Ehe/m_s	Hard scoured bedrock or firm mud outcrops/mounds and depressions in estuary

Table 2. Region and induration specific area of habitat types interpreted from remote sensing imagery. Area was determined using the Feature Geometry Calculator extension in ArcView™ on data projected in UTM Zone 10, NAD 83

Region	Data Type	Area (km ²)	Soft (km ²)	Mixed (km ²)	Hard (km ²)
USGS	Multibeam	44.24	39.90	0.00	4.34
h10896	Multibeam	10.38	10.31	0.06	<0.01
h10960	Multibeam	29.22	29.22	0.00	0.00
h10961	Multibeam	7.84	7.84	0.00	0.00
h10962	Multibeam	28.60	28.46	0.11	0.03
Region A	Side-scan	7.85	7.72	0.12	0.00
Region B	Side-scan	10.46	10.37	0.09	<0.01
Region C	Side-scan	2.82	2.43	0.39	<0.01
Region E	Side-scan	28.92	18.55	10.25	0.12
	TOTALS	170.32	154.80	11.02	4.50
	% TOTALS	100.00	90.89	6.47	2.64

**Grain size analysis of U.S. Geological Survey sediment grab samples
(SFB-98-1 to SFB-98-56) for the purpose of benthic habitat identification
in San Francisco Bay, California**

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Introduction

Geophysical seafloor imagery (side-scan sonar and multibeam bathymetry) within the San Francisco Bay area are being analyzed and interpreted into marine benthic habitat maps using the methodology described in Greene et al, 1999. To aid in the interpretation of these images, 56 surface sediment grab samples collected in the San Francisco Bay region by the U.S. Geological Survey (USGS) were analyzed at the USGS Marine Sediment Lab (MSL) in Menlo Park, California for grain size characteristics following USGS MSL standards. MSL standards are based on the work of Carver (1971), Folk (1974), Folk & Ward (1957), Inman (1952), Krumbein & Pettijohn (1938), and Trask (1930). The grain size analyses provided geographically located physical evidence of seafloor surface substrate; a valuable tool when displayed over the geophysical imagery and interpretations.

Methods

With the guidance of Dr. Jon Chin, Mike Torresan and Simon Barber of the MSL at the USGS, the appropriate San Francisco Bay sediment grab samples were located and organized. Sample grain size data were merged with the shapefile “usgs_cores.shp” using ESRI’s ArcView GIS 3.3® in order to map the locations of the samples in the San Francisco Bay. The location shapefile is in the compact disk “San Francisco Bay Watershed Database and Mapping Project” developed by NOAA. One sediment sample was missing (station ID 9) from the expected 56 sample total and 13 samples had duplicates. Two alternate samples (10A and 17A) replaced samples 10 and 17. A station location was not provided for sample 29 in the shapefile “usgs_cores.shp”. The sample was in storage with the other San Francisco Bay sediment samples and was processed for grain size data, but could not be mapped with the other samples. There was one location given in “usgs_cores.shp” where no station identification number was given. This may be the location for sample 29, but there is no way to confirm if this is the case (Figure 1 & Table 1).

The samples were processed in three separate groups (with one duplicate sample analyzed for each batch, denoted with an R next to the station ID (samples 5, 54, and 56). Samples were analyzed to half phi intervals ranging from greater than -1 phi (2.00 mm) to 11 phi (0.00049 mm) and at 14 phi (0.00006). Samples were separated by wet sieving at -1 phi (2.00 mm), -0.5 phi (1.4 mm), and 0 phi (1.00 mm) grain diameters. Sample grain diameters below 0 phi (1.00 mm) were analyzed using a Beckman Coulter Light Scattering (LS) particle analyzer. The sieve data and the data produced using the Beckman Coulter LS particle analyzer were combined to produce an over all grain size distribution and descriptive statistics for each individual sample using SedSize, a USGS developed Unix based computer program. Using the Folk and Ward (1957) mean grain diameter calculated by SedSize, the samples were categorized into Wentworth size classes (Wentworth, 1922) (Table 2). For a detailed description of sediment sample preparation and grain size analysis techniques,

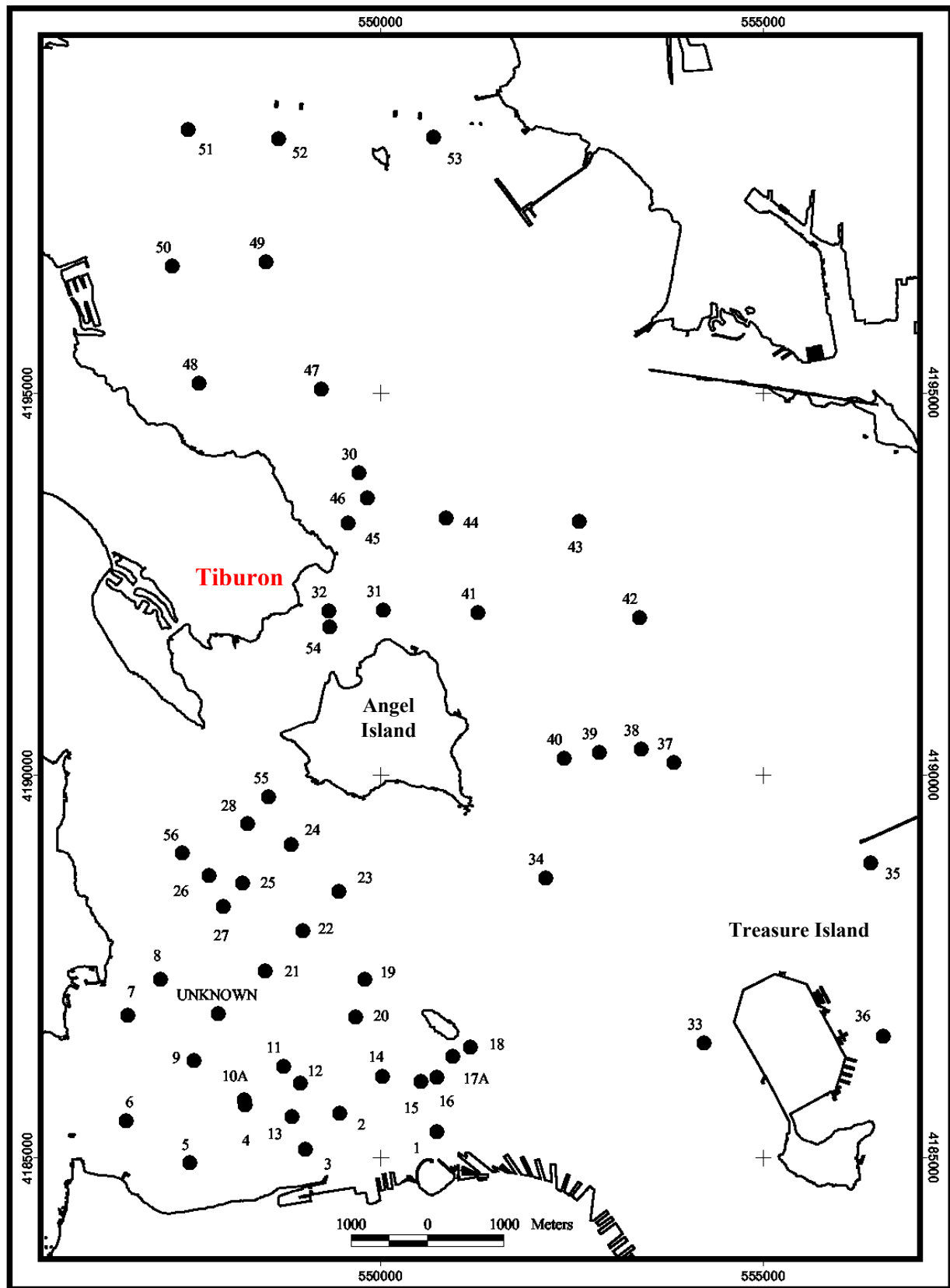


Figure 1. Location of the 56 USGS collected sediment grab samples within the San Francisco Bay. “Unknown” refers to the extra sample location in the USGS station ID shapefile. Sample 29 is not mapped because it has no location information.

Station ID	Folk & Ward mean (phi)	Wentworth Size Class	Northing	Easting
1	-0.26	Very Coarse Sand (w/shells)	550727.96274	4185338.01382
2	1.64	Medium Sand	549457.23136	4185577.70227
3	2.16	Fine Sand	549004.09276	4185106.76479
4	1.78	Medium Sand	548214.65502	4185682.38741
5	4.71	Coarse Silt	547501.67084	4184925.97382
5R	4.07	Coarse Silt	547501.67084	4184925.97382
6	1.4	Medium Sand	546660.53783	4185475.92639
7	-0.49	Very Coarse Sand	546685.24888	4186859.65646
8	2.26	Fine Sand	547113.82459	4187322.55930
9	Missing sample	Missing sample	547556.42374	4186265.49959
10A	1.5	Medium Sand	548211.63081	4185747.83238
11	0.1	Coarse Sand	548720.36892	4186194.64588
12	1.08	Medium Sand	548944.40195	4185966.30166
13	1.97	Medium Sand	548829.01407	4185536.22432
14	1.71	Medium Sand	550010.58408	4186060.37014
15	6.26	Fine Silt	550513.54094	4185996.87170
16	6.05	Fine Silt	550728.00429	4186044.79266
17A	2.57	Fine Sand	550934.90241	4186319.01933
18	1.08	Medium Sand	551161.18612	4186445.80269
19	0.24	Coarse Sand	549782.00845	4187324.97084
20	0.29	Coarse Sand	549665.30680	4186831.62799
21	0.63	Coarse Sand	548476.31318	4187432.55921
22	0.27	Coarse Sand	548978.26896	4187963.67693
23	1.38	Medium Sand	549440.69284	4188473.50745
24	1.05	Medium Sand	548819.36567	4189086.69875
25	0.23	Coarse Sand (w/shells)	548190.61538	4188581.47329
26	0.42	Coarse Sand (w/shells)	547747.45919	4188680.96392
27	-0.15	Very Coarse Sand	547938.11312	4188275.98196
28	1.9	Medium Sand	548251.16248	4189358.50859
29	0.44	Coarse Sand	Missing location	Missing location
30	0.6	Coarse Sand	549705.78287	4193954.06346
31	1.83	Medium Sand	550025.41289	4192150.76291
32	0.39	Coarse Sand (w/shells)	549309.56717	4192139.77350
33	7.08	Very Fine Silt	554217.51959	4186493.12668
34	5.8	Medium Silt	552144.34901	4188653.32390
35	6.32	Fine Silt	556396.39845	4188844.51449
36	6.86	Fine Silt	556553.61503	4186583.20313
37	4.57	Coarse Silt	553824.73586	4190158.73187
38	5.65	Medium Silt	553393.35836	4190342.32142
39	5.46	Medium Silt	552847.37972	4190293.29792
40	3.08	Very Fine Sand	552384.26850	4190215.99060
41	4.34	Very Fine Sand	551262.18592	4192119.56023
42	6.17	Fine Silt	553370.78491	4192055.33218
43	4.98	Coarse Silt	552589.62188	4193314.07703
44	5.61	Medium Silt	550849.92787	4193359.69710
45	0.15	Coarse Sand	549569.10154	4193290.83283
46	1.26	Medium Sand	549817.69325	4193625.20473
47	0.8	Coarse Sand (w/shells)	549211.21465	4195046.21144
48	6.41	Fine Silt	547618.59444	4195117.80489
49	5.17	Medium Silt	548492.74942	4196709.59227
50	6.52	Fine Silt	547269.51561	4196650.29625
51	5.9	Medium Silt	547477.15016	4198437.88150
52	1.09	Medium Sand	548655.51313	4198312.75921
53	3.2	Very Fine Sand	550681.07598	4198338.35686
54	1.57	Medium Sand	549325.73167	4191937.93247
54R	2.08	Fine Sand	549325.73167	4191937.93247
55	1.33	Medium Sand	548529.70952	4189715.20365
56	1.36	Medium Sand	547395.57559	4188975.17396
56R	1.18	Medium Sand	547395.57559	4188975.17396
No ID	Unknown	Unknown	547867.02592	4186884.20488

Table 1. Grain size parameters used to aid in benthic habitat interpretations of San Francisco Bay geophysical seafloor imagery. Where shells were present in the samples, they were included with the Wentworth size class of the sediment sample. There was no sediment sample for station ID 9. A station location was not provided for sample 29. One location within the shapefile “usgs_cores.shp” did not have a station ID and is shown on the bottom of the table.

Phi diameter	mm diameter	Classification
< -8.0	> 256	boulder
-6.0 to -8.0	64 to 256	cobble
-2.0 to -6.0	4.00 to 64	pebble
-1.0 to -2.0	2.00 to 4.00	granule
0.0 to -1.0	1.00 to 2.00	very coarse sand
1.0 to 0.0	0.50 to 1.00	coarse sand
2.0 to 1.0	0.25 to 0.50	medium sand
3.0 to 2.0	0.125 to 0.25	fine sand
4.0 to 3.0	0.0625 to 0.125	very fine sand
5.0 to 4.0	0.031 to 0.0625	coarse silt
6.0 to 5.0	0.0156 to 0.031	medium silt
7.0 to 6.0	0.0078 to 0.0156	fine silt
8.0 to 7.0	0.0039 to 0.0078	very fine silt
> 8.0	< 0.0039	clay

Table 2. Break down of Wentworth grain size classification based on Folk and Ward (1957) mean grain diameter in phi and millimeter.

see Appendix A and for individual grain size distributions and statistical parameters, see Appendix B.

Results

The 56 USGS sediment grab samples were mapped according to individual Wentworth size classes along with a note about whether or not the sample contained large amounts of shell debris and geographically displayed over multibeam images collected by the USGS, and other multibeam and side-scan sonar imagery supplied by NOAA NOS using GIS. The samples provide physical evidence or “ground truth” of seafloor surface substrate to aid in the interpretation of the geophysical images. An example of how the sediment data is displayed over a multibeam image is shown in Figure 2.

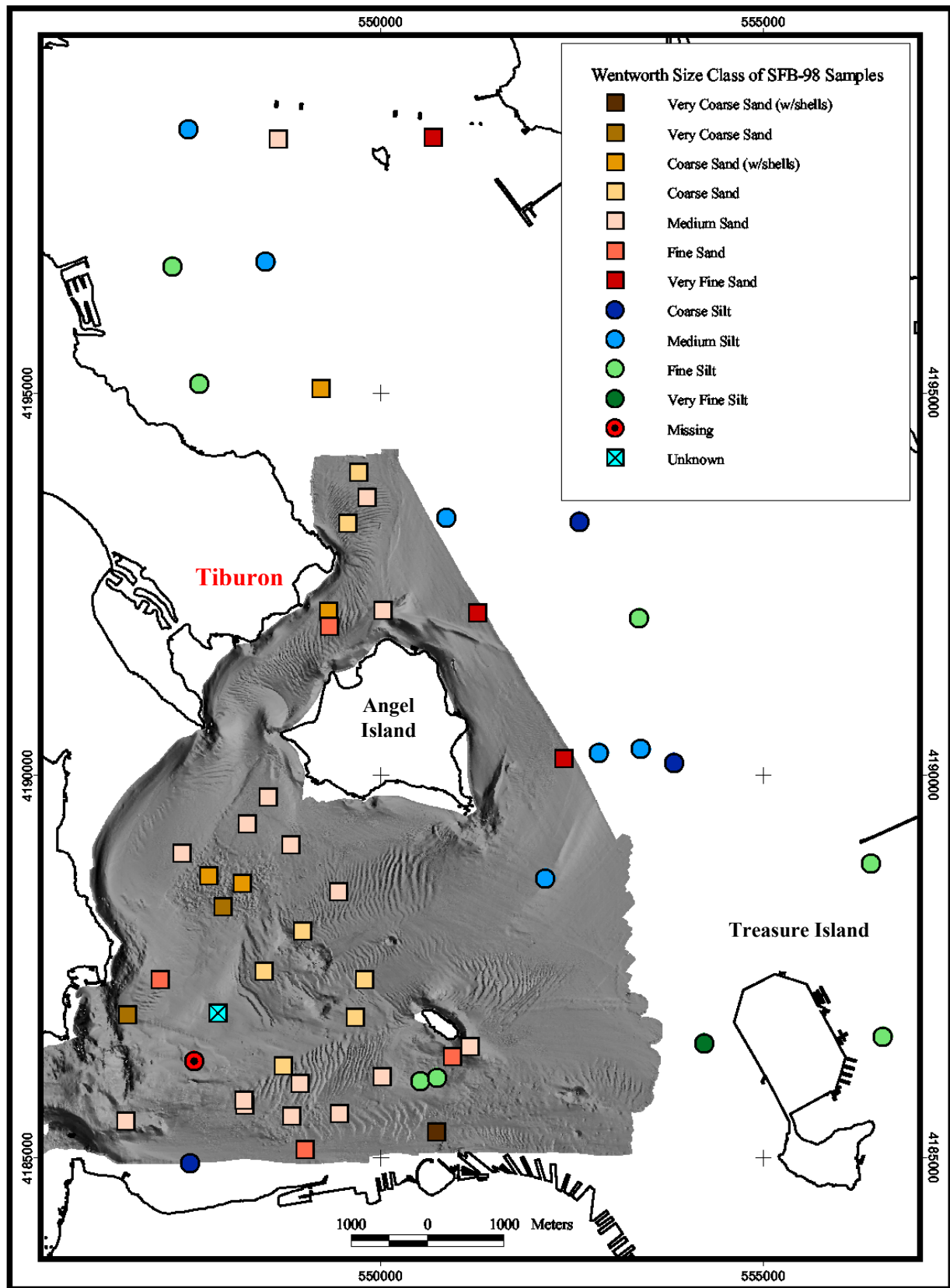


Figure 2. Example of geographically located grain size data displayed over a San Francisco Bay area multibeam image produced by the USGS. “Missing” sample location refers to sample 9 and “unknown” refers to the sample location in the shapefile “usgs_cores.shp” that does not have a station ID. Sample 29 does not have a station location and is not mapped.

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Appendix A.
Sediment Sample Analysis Protocol (USGS MSL)

1. Sample Preparation

- Mix each individual sample thoroughly to homogenize
- Add representative sample to a 1000 ml beaker
- Add 100-200ml of DI water and stir sample to completely disaggregate sediment grains
- Add 5-10 ml of 30% hydrogen peroxide to oxidize any organic matter, let stand over night
- Gently boil off hydrogen peroxide for 2-4 hours, adding DI water if necessary
- Wash entire sample into a pre-labeled 250 ml centrifuge bottle. Place samples in centrifuge, making sure to balance the weight across the centrifuge in pairs. Use DI water to equalize weights so that the centrifuge will not vibrate. Run centrifuge, slowly turning the speed up to 36 rpm, for 30 minutes. Removed sample and decanted water to remove excess soluble salts.
- Add DI water and mix sample repeating the centrifuge process for an 60 additional minutes. Decant excess water, removing soluble salts.

2. Wet Sieving

- Rinse sample from centrifuge tubes over a 2mm, 1.4mm and 1mm sieves and a funnel using DI water into a pre-labeled 1000ml graduated cylinder, saving the less than 1mm portion of the sample in the cylinder for analyzing by the Beckman Coulter LS Particle Size Analyzer.
- Place the sieved coarse fraction (>2mm gravels) on a pre-labeled drying dish and place in oven
- Place the sieved intermediate (2mm to 1.4 mm sands) on a pre-labeled drying dish and place in oven.
- Place sand fraction (1.4mm to 1mm sands) on a pre-labeled drying dish and place in oven.
- Weigh all sieve fractions when completely dry to apply in the SedSize grain size analysis program

3. Coulter Counter (processing the <1mm sediment sample fraction)

- Weigh and record three metal weighing tins using gloves to keep from affecting the weight
- Add 10 ml of Calgon dispersing solution to each tin.
- Dry tins, subtract from the original tin weight to find the weight of Calgon then average the three weights to subtract from the <1mm sample weight later.
- Add 10 ml of the Calgon solution to the less than 1mm sediment sample collected in the graduated cylinders. This will disperses the clays and keep them from sticking together. Bring level of cylinder to 1000ml using DI water and agitate sample to disperse Calgon uniformly throughout the sample. Let stand over night.

- The following day, use latex gloves to label and weigh 1000ml beaker and added entire dispersed sample from 1000ml-graduated cylinder. Place under mechanical agitator and mix sample.
- Running the Beckman Coulter LS Particle Analyzer
- Turn on tap water in sink connected to the Coulter Counter. It doesn't have to be on hard. Remove yellow lid where you add sample.
- From the adjacent computer, click on "Coulter Counter" desktop icon. Use 'optical module'. From the Control menu click "pump on", then "rinse". Wipe out the reservoir with a paper towel to remove any residual sediment. Then click "open drain" to clear the water then "close drain".
- Fill with deoxygenated DI water available in carboys opposite the machine. Fill reservoir between the second and third sensors. The water should be swirling in the reservoir. If not you must manually open the valve, siphon out the air lock, manually close the drain, and add more water until it is visibly swirling. If you add too much water, manually open the drain and let some out.
- From the Preferences menu choose "Preference Files" then "Load Preferences". Find the appropriate preference file from the Preference files folder. In our case, the file will run the analysis three times.
- From the "Run" menu choose "Run Cycle". Turn off the "Auto Rinse" and click "New Sample" then "Start". The computer should start by measuring background noise, etc. When the screen displays the message "low add sample" begin adding sample to the swirling water reservoir.
- Pipette sample from the still agitating sample into the water reservoir until the computer message says "O.K.", when the obscuration rate is between 8% and 12%.
- Type in the sample ID number, etc in the spaces provided and run the sample.
- After the sample is run, overlay the graphs of the three sample runs and average for the final grain size distribution. Print results and save for later use in the SedSize program.
- Drain the sample from the Coulter Counter and recombine with the sample in the 1000 ml beaker. Dry the sample completely in the oven over night and weigh for a total fine sample weight.

4. SedSize (combining fine and coarse sediment data)

- SedSize is a Unix based program that combines weights of the greater than 1mm fraction with percentages of the less than 1 mm to produce an over all grain size distribution. The program automatically calculates mean, sorting, skewness and kurtosis using a variety of methods as well as the percentages of sand, silt and clay present in the samples. The program also produces ratios of gravel, sand silt and clay as well.

Appendix B.

Grain size distributions and descriptive statistical parameters

SFBay-98 USGS grain size samples 1 – 14
(Sample 9 missing)

	1	2	3	4	5	5R	6	7	8	10A	11	12	13	14
Phi	-1	62.18	0	0	0	0	0	35.76	1.66	0	20.87	1.38	0	0
	-0.5	1.32	0	0	0	0.18	0.11	0.11	13.52	2.65	0	8.8	0.41	0
	0	0.53	0.18	0	0	0.29	0.23	0.26	15.15	2.56	0	11.63	0.41	0
	0.5	2.46	4.18	0	0	0	0	6.97	21.64	4.43	4.1	15.79	8.27	0
	1	2.43	7.7	0.03	1.52	0.01	0.01	14.84	10.69	8.7	11.4	17.85	31.43	0.32
	1.5	10.22	28.75	7.61	24.88	1.11	1.65	36.46	2.06	15.37	33.9	15.15	41.56	13.28
	2	10.36	36.54	32.16	44.5	8.23	11.99	27.4	0.64	15.37	35.4	4.93	14.96	39.4
	2.5	5.65	18.07	39.8	23.3	18.51	24.81	8.87	0.28	16.48	13.4	1.88	0.98	34.7
	3	1.4	2.89	14.5	2.8	13.64	16.74	2.09	0.11	11.45	1.5	0.76	0.59	8.3
	3.5	0.29	0.5	1.5	0.5	5.47	5.48	0.6	0.04	3.63	0.3	0.29	0	0.9
	4	0.18	0.3	0.7	0.4	4.58	3.89	0.2	0	1.77	0	0.18	0	0.4
	4.5	0.18	0.1	0.3	0.2	4.68	3.79	0.2	0.04	1.68	0	0.23	0	0.3
	5	0.22	0.1	0.3	0.2	4.08	3.09	0.2	0	1.49	0	0.23	0	0.3
	5.5	0.22	0.1	0.3	0.2	3.38	2.49	0.1	0	1.3	0	0.18	0	0.2
	6	0.18	0	0.2	0.1	3.38	2.39	0.2	0.04	1.21	0	0.18	0	0.2
	6.5	0.25	0.1	0.3	0.2	3.38	2.39	0.2	0	1.21	0	0.12	0	0.2
	7	0.25	0.1	0.3	0.1	3.58	2.59	0.1	0	1.21	0	0.18	0	0.2
	7.5	0.29	0.1	0.3	0.2	3.98	2.79	0.2	0.02	1.21	0	0.12	0	0.2
	8	0.32	0.1	0.3	0.2	4.18	2.99	0.2	0.01	1.3	0	0.12	0	0.2
	8.5	0.29	0.1	0.3	0.2	4.08	2.89	0.2	0	1.3	0	0.18	0	0.2
	9	0.25	0	0.3	0.2	3.48	2.59	0.2	0	1.12	0	0.12	0	0.2
	9.5	0.22	0.07	0.3	0.2	2.89	2.29	0.2	0	1.02	0	0.12	0	0.2
	10	0.14	0.03	0.2	0.06	2.69	1.99	0.1	0	0.84	0	0.06	0	0.2
	10.5	0.11	0	0.2	0.03	2.19	1.49	0.08	0	0.56	0	0.05	0	0.08
	11	0.06	0	0.08	0.01	1.59	1	0.02	0	0.37	0	0.01	0	0.02
	14	0.01	0	0.02	0	0.4	0.3	0	0	0.09	0	0	0	0
% Gravel		62.18	0	0	0	0	0	35.76	1.66	0	20.87	1.38	0	0
% Sand		34.83	99.1	96.3	97.9	52.02	64.92	97.81	64.13	82.41	100	77.25	98.62	97.3
% Silt		1.91	0.7	2.3	1.4	30.66	22.52	1.39	0.1	10.62	0	1.35	0	1.8
% Clay		1.08	0.2	1.4	0.7	17.32	12.56	0.8	0	5.31	0	0.53	0	0.9
% Mud		2.99	0.9	3.7	2.1	47.98	35.08	2.19	0.11	15.92	0	1.88	0	2.7
Gravel/Sand		1.79	0	0	0	0	0	0.56	0.02	0	0.27	0.01	0	0
Sand/Silt		18.27	141.82	41.87	69.93	1.7	2.88	70.12	621.8	7.76	0	57.21	0	54.06
Silt/Clay		1.77	3.5	1.64	2	1.77	1.79	1.75	28.95	2	0	2.56	0	2
Sand/Clay		32.28	496.41	68.79	139.86	3	5.17	122.71	n/a	15.53	0	146.21	0	108.11
Sand/Mud		11.67	110.31	26.03	46.62	1.08	1.85	44.62	601.04	5.18	0	41.12	0	36.04
Gravel/Mud		20.83	0	0	0	0	0	0	335.13	0.1	0	11.11	0	0
1st moment		-0.06	1.64	2.3	1.88	4.74	4.08	1.5	-0.4	2.48	1.49	0.3	1.05	2.1
Variance		3.59	0.57	1.28	0.81	7.56	6.67	1.12	0.68	5.42	0.28	1.89	0.3	0.94
Std. deviation		1.89	0.76	1.13	0.9	2.75	2.58	1.06	0.82	2.33	0.53	1.37	0.54	0.97
3rd moment		2.18	3.27	4.43	5.1	0.66	1.1	4.21	0.98	1.56	-0.13	2.23	-0.97	4.82
4th moment		9.55	29.67	26.65	37.24	2.21	3.03	28.81	6.73	5.42	3.14	13.7	6.72	33.06
F&W median		-1.1	1.6	2.07	1.76	3.77	2.74	1.42	-0.47	1.98	1.5	0.29	1.05	1.99
F&W mean		-0.26	1.64	2.16	1.78	4.71	4.07	1.4	-0.49	2.26	1.5	0.1	1.08	1.97
F&W sorting		1.36	0.55	0.51	0.49	2.72	2.49	0.6	0.8	2.07	0.47	1.13	0.47	0.45
F&W skewness		0.82	0.01	0.26	0.09	0.48	0.76	-0.02	0.06	0.36	-0.14	-0.13	0.03	-0.04
F&W kurtosis		0.59	1.31	1.66	1.05	0.72	0.91	1.39	0.61	2.23	1.03	0.8	1.47	1.43
I. median		-1.1	1.6	2.07	1.76	3.77	2.74	1.42	-0.47	1.98	1.5	0.29	1.05	1.99
I. mean		0.17	1.66	2.21	1.79	5.18	4.73	1.39	-0.49	2.4	1.5	0	1.09	1.97
I. sorting		1.54	0.52	0.45	0.5	2.98	2.69	0.54	0.93	1.58	0.48	1.2	0.42	0.42
I. skewness 1		0.82	0.11	0.3	0.05	0.47	0.74	-0.05	-0.02	0.27	-0.01	-0.24	0.1	-0.05
I. skewness 2		1.04	-0.18	0.48	0.2	0.67	1.09	0.01	0.17	1.2	-0.4	-0.02	-0.06	-0.07
I. kurtosis		0.28	0.82	1.15	0.59	0.37	0.41	1.02	0.19	1.68	0.53	0.44	1.03	0.87
T. median		2.14	0.33	0.24	0.3	0.07	0.15	0.37	1.39	0.25	0.35	0.82	0.48	0.25
T. mean		1.41	0.32	0.22	0.3	0.1	0.12	0.4	1.64	0.29	0.36	1.1	0.47	0.26
T. sorting		2.6	1.23	1.18	1.24	4.97	3.25	1.25	1.68	1.71	1.23	1.85	1.18	1.17
T. skewness		0.2	0.92	0.87	0.97	0.26	0.19	1.06	1.08	1.01	0.99	1.28	0.92	1.07
T. kurtosis		0.43	0.22	0.19	0.28	0.36	0.34	0.21	0.36	0.19	0.21	0.27	0.18	0.18

SFBay-98 USGS grain size samples 15 - 27

	15	16	17A	18	19	20	21	22	23	24	25	26	27	
Phi	-1	3.1	2.36	31.77	24.83	0	34.83	3.01	35.07	0.4	1.61	48.45	35.17	24.12
	-0.5	0.24	0.7	2.12	1.83	18.2	5.48	4.24	0	0.4	2.17	0.24	3.3	11.67
	0	0.16	0.91	1.24	0	22.52	3.54	8.2	0.51	1.08	4.28	0.21	2.55	16.04
	0.5	0	0	1.76	3.59	22.35	7.92	27.82	10.37	7.39	17.83	10.53	6.31	20.28
	1	0	0	3.35	0.89	18.73	9.38	28.24	18.36	14.39	22.89	6.29	6.67	15.46
	1.5	0.01	0.26	8.19	8.58	10.31	15.27	18.85	21.26	33.07	25.37	7.15	15.93	8.33
	2	1.66	5.14	8.04	18.99	4.56	14.26	7.36	10.76	30.32	16.27	11.7	19.94	2.99
	2.5	4.79	5.17	5.25	23.54	2.31	6.91	1.69	2.58	10.2	6.8	10.53	9.02	0.67
	3	2.33	1.25	2.34	9.39	0.71	1.74	0.34	0.58	1.47	2.02	3.58	0.94	0.29
	3.5	4.54	2.5	1.17	1.54	0.12	0.28	0.08	0.19	0.49	0.28	0.51	0.18	0.05
	4	5.79	3.94	1.23	0.59	0.06	0.06	0.08	0	0.2	0.09	0.26	0	0
	4.5	6.47	5.95	1.69	0.51	0	0.06	0	0.06	0	0.09	0.1	0	0.05
	5	6.56	6.82	2.21	0.51	0.06	0.06	0	0	0.1	0	0.1	0	0
	5.5	5.5	6.15	2.47	0.51	0	0	0	0.06	0.1	0.09	0.05	0	0
	6	5.11	5.86	2.72	0.44	0	0	0	0	0	0	0.05	0	0.02
	6.5	5.31	5.86	2.98	0.44	0.04	0.06	0.06	0.06	0.1	0	0.05	0	0.02
	7	5.79	6.24	3.05	0.51	0.01	0	0.02	0.06	0	0.09	0.05	0	0
	7.5	6.66	6.91	3.24	0.51	0.01	0.06	0.01	0	0.1	0	0.05	0	0
	8	7.14	7.3	3.31	0.51	0	0	0	0	0.1	0	0	0	0
	8.5	6.95	6.72	3.05	0.51	0	0.06	0	0.04	0	0.06	0.05	0	0
	9	5.98	5.67	2.59	0.51	0	0	0	0.01	0.05	0.02	0.03	0	0
	9.5	5.02	4.61	2.08	0.44	0	0.04	0	0.01	0.03	0.01	0.02	0	0
	10	4.25	3.84	1.75	0.37	0	0.01	0	0.01	0.02	0.01	0.01	0	0
	10.5	3.57	3.17	1.36	0.22	0	0	0	0	0	0	0	0	0
	11	2.41	2.11	0.78	0.15	0	0	0	0	0	0	0	0	0
	14	0.68	0.58	0.26	0.07	0	0	0	0	0	0	0	0	0
% Gravel	3.1	2.36	31.77	24.83	0	34.83	3.01	35.07	0.4	1.61	48.45	35.17	24.12	
% Sand	19.51	19.86	34.69	68.94	99.88	64.83	96.91	64.61	99.01	98.02	50.99	64.83	75.78	
% Silt	48.54	51.09	21.67	3.96	0.12	0.22	0.08	0.26	0.49	0.28	0.46	0	0.1	
% Clay	28.85	26.7	11.87	2.27	0	0.11	0	0.06	0.1	0.09	0.1	0	0	
% Mud	77.39	77.78	33.54	6.23	0.12	0.34	0.08	0.32	0.59	0.37	0.56	0	0.1	
Gravel/Sand	0.16	0.12	0.92	0.36	0	0.54	0.03	0.54	0	0.02	0.95	0.54	0.32	
Sand/Silt	0.4	0.39	1.6	17.41	850.94	288.64	1146.3	250.72	201.81	355.42	110.87	0	786.5	
Silt/Clay	1.68	1.91	1.83	1.74	98.62	2	n/a	4	5	3	4.5	0	n/a	
Sand/Clay	0.68	0.74	2.92	30.32	n/a	577.37	n/a	1002.9	1009.1	1066.1	499.01	n/a	n/a	
Sand/Mud	0.25	0.26	1.03	11.06	842.39	192.44	1146.2	200.58	168.18	266.55	90.71	n/a	786.56	
Gravel/Mud	0.04	0.03	0.95	3.98	0	103.39	35.56	108.87	0.68	4.38	86.19	n/a	250.39	
1st moment	6.14	6	2.57	1.44	0.3	0.28	0.61	0.28	1.39	1.01	0.16	0.38	-0.08	
Variance	7.74	7.93	13.92	4.66	0.68	1.91	0.56	1.57	0.59	0.74	2.36	1.87	0.86	
Std. deviation	2.78	2.82	3.73	2.16	0.82	1.38	0.75	1.25	0.77	0.86	1.54	1.37	0.92	
3rd moment	-0.42	-0.44	0.6	1.14	0.96	0.48	0.25	0.23	2.16	0.88	0.69	-0.07	0.46	
4th moment	2.93	2.8	2.04	6.13	5.46	3.63	6.43	3.68	23	10.79	3.12	1.38	3.34	
F&W median	6.36	6.26	1.58	1.83	0.2	0.43	0.61	0.63	1.43	1.02	0.05	0.71	-0.05	
F&W mean	6.26	6.05	2.57	1.08	0.24	0.29	0.63	0.27	1.38	1.05	0.23	0.42	-0.15	
F&W sorting	2.64	2.74	3.78	1.94	0.8	1.29	0.67	1.13	0.58	0.72	1.43	1.34	0.96	
F&W skewness	-0.06	-0.1	0.39	-0.29	0.13	-0.09	-0.04	-0.28	-0.2	0	0.2	-0.22	-0.06	
F&W kurtosis	0.83	0.91	0.63	0.85	0.95	0.57	1.27	0.52	1.17	1	0.57	0.56	0.77	
I. median	6.36	6.26	1.58	1.83	0.2	0.43	0.61	0.63	1.43	1.02	0.05	0.71	-0.05	
I. mean	6.21	5.95	3.06	0.71	0.25	0.22	0.64	0.09	1.35	1.06	0.32	0.27	-0.2	
I. sorting	2.78	2.89	4.31	1.89	0.81	1.49	0.62	1.36	0.57	0.67	1.66	1.54	1.05	
I. skewness 1	-0.05	-0.11	0.34	-0.59	0.07	-0.14	0.05	-0.4	-0.15	0.06	0.16	-0.28	-0.14	
I. skewness 2	-0.1	-0.14	0.54	0.04	0.32	-0.04	-0.25	-0.19	-0.44	-0.1	0.28	-0.18	0.03	
I. kurtosis	0.49	0.48	0.24	0.75	0.62	0.2	0.92	0.09	0.72	0.88	0.19	0.2	0.36	
T. median	0.01	0.01	0.33	0.28	0.87	0.74	0.66	0.64	0.37	0.49	0.96	0.61	1.03	
T. mean	0.03	0.03	1.09	1.03	0.92	1.28	0.66	1.32	0.4	0.54	1.35	1.27	1.31	
T. sorting	4.12	3.81	11.36	3.02	1.48	2.46	1.31	2.27	1.27	1.43	2.68	2.58	1.7	
T. skewness	1.19	1.1	0.32	4.76	0.97	1.45	0.93	2.29	1.09	1.04	0.84	1.97	1.23	
T. kurtosis	0.15	0.1	0.42	0.36	0.27	0.4	0.2	0.4	0.2	0.28	0.42	0.41	0.3	

SFBay-98 USGS grain size samples 28 - 42

	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Phi	-1	2.07	6.83	8.46	0	46.25	0	0	0	0	0	0	0	0.5	0
	-0.5	0.94	4.13	3.76	0	0.96	0	0	0	0	0	0	0	0.04	0
	0	1.48	9.96	4.03	0	0.9	0	0	0	0	0	0	0	0.03	0
	0.5	6.15	32.9	24.96	0	5.86	0	0	0	0	0	0	0.57	0	0
	1	3.59	27.83	30.24	0.56	6.28	0	0	0	0.09	0	0.11	0.01	0.16	0
	1.5	9.17	13.36	20.02	19.34	10.12	0	0	0	1.31	0.01	0.95	5.01	1.8	0.02
	2	25.59	3.56	5.7	42.5	11	0	0.13	0.65	0	2.73	0.74	2.4	26.71	9.48
	2.5	33.43	0.87	1.68	29.1	9.81	0	5.1	4.88	0	7.08	2.98	8.24	36	20.78
	3	14.71	0.4	0.92	6	3.42	0.01	10.27	7.17	0.54	15.3	6.37	9.5	9.7	14.02
	3.5	1.53	0	0.08	0.6	0.88	1.02	7.5	5.5	3.21	18.1	11	7.6	1.7	5.77
	4	0.48	0.08	0	0.3	0.57	4.78	7.7	4.9	6.45	13.8	11.9	7.8	1.3	4.57
	4.5	0.1	0	0.08	0.2	0.57	6.99	7.1	5.5	7.1	8.7	9.9	7.5	1.2	4.57
	5	0.19	0	0	0.1	0.42	7.2	6.1	5.6	7.3	4.9	6.9	6	1.3	4.47
	5.5	0	0	0	0.1	0.31	6.5	5	4.9	6.2	3	4.8	4.6	1.3	3.78
	6	0.1	0	0	0.1	0.26	6.4	4.8	4.9	6	2.4	4.3	4.2	1.2	3.28
	6.5	0.1	0.05	0.07	0.1	0.26	6.8	4.9	5.3	6.3	2.3	4.3	4.1	1.4	3.08
	7	0	0.02	0.02	0.2	0.31	7.3	5.2	6	7	2.5	4.5	4.4	1.4	3.18
	7.5	0.1	0.01	0	0.1	0.26	8.1	5.8	6.8	8	2.6	5	4.9	1.7	3.38
	8	0.1	0	0	0.2	0.31	8.8	6.1	7.4	8.6	2.8	5.2	5.2	1.8	3.48
	8.5	0.1	0	0	0.1	0.31	8.4	5.8	7.1	8.1	2.7	5	5	1.8	3.18
	9	0	0	0	0.2	0.31	7.4	5	6.1	7	2.4	4.4	4.3	1.5	2.68
	9.5	0.07	0	0	0.1	0.21	6.2	4.2	5.2	5.7	2.2	3.8	3.8	1.4	2.39
	10	0.02	0	0	0.09	0.21	5.5	3.6	4.6	4.9	2	3.5	3.5	1.2	2.09
	10.5	0	0	0	0.01	0.1	4.6	3.1	4	4.1	1.7	2.9	3.1	1	1.79
	11	0	0	0	0	0.09	3.1	2	2.7	2.7	1.1	1.9	2.2	0.6	1.19
	14	0	0	0	0	0.02	0.9	0.6	0.8	0.8	0.3	0.6	0.6	0.2	0.3
% Gravel	2.07	6.83	8.46	0	46.25	0	0	0	0	0	0	0	0	0.5	0
% Sand	97.07	93.09	91.38	98.4	49.81	5.81	30.7	23.1	10.2	58.4	33	36.6	81	56.65	22.9
% Silt	0.67	0.08	0.17	1.1	2.7	58.09	45	46.4	56.5	29.2	44.9	40.9	11.3	29.23	50.7
% Clay	0.19	0	0	0.5	1.25	36.1	24.3	30.5	33.3	12.4	22.1	22.5	7.7	13.62	26.4
% Mud	0.86	0.08	0.17	1.6	3.94	94.19	69.3	76.9	89.8	41.6	67	63.4	19	42.85	77.1
Gravel/Sand	0.02	0.07	0.09	0	0.93	0	0	0	0	0	0	0	0	0.01	0
Sand/Silt	145.19	1177.4	545.47	89.45	18.46	0.1	0.68	0.5	0.18	2	0.73	0.89	7.17	1.94	0.45
Silt/Clay	3.5	3454.3	n/a	2.2	2.17	1.61	1.85	1.52	1.7	2.35	2.03	1.82	1.47	2.15	1.92
Sand/Clay	508.23	n/a	n/a	196.8	39.99	0.16	1.26	0.76	0.31	4.71	1.49	1.63	10.52	4.16	0.87
Sand/Mud	112.93	1177	545.49	61.5	12.63	0.06	0.44	0.3	0.11	1.4	0.49	0.58	4.26	1.32	0.3
Gravel/Mud	2.41	86.41	50.48	0	11.73	0	0	0	0	0	0	0	0	0.01	0
1st moment	1.85	0.42	0.57	1.95	0.43	7.12	5.88	6.37	6.89	4.53	5.71	5.55	3.13	4.38	6.18
Variance	0.99	0.58	0.72	0.66	4	4.21	6.31	6.43	4.56	5.34	5.97	7	5.24	6.95	5.73
Std. deviation	1	0.76	0.85	0.81	2	2.05	2.51	2.54	2.13	2.31	2.44	2.65	2.29	2.64	2.39
3rd moment	0.18	0.18	-0.12	5.12	1.61	0.09	0.3	0.01	0.08	1.17	0.51	0.39	1.9	0.83	0.22
4th moment	10.95	6.89	5.26	40.81	7.12	2.17	1.98	1.97	2.14	3.44	2.16	2.03	5.53	2.63	2.05
F&W median	2.01	0.48	0.64	1.88	0.42	7.19	5.61	6.56	6.99	3.67	5.02	4.99	2.12	3.26	6.01
F&W mean	1.9	0.44	0.6	1.83	0.39	7.08	5.8	6.32	6.86	4.57	5.65	5.46	3.08	4.34	6.17
F&W sorting	0.75	0.7	0.76	0.46	1.55	2.13	2.58	2.65	2.2	2.29	2.45	2.69	1.93	2.56	2.43
F&W skewness	-0.36	-0.18	-0.19	-0.05	0.08	-0.04	0.14	-0.09	-0.05	0.58	0.36	0.26	0.84	0.61	0.1
F&W kurtosis	1.32	1.49	2.13	1.57	0.65	0.8	0.72	0.76	0.79	1.2	0.75	0.72	3.97	0.81	0.76
I. median	2.01	0.48	0.64	1.88	0.42	7.19	5.61	6.56	6.99	3.67	5.02	4.99	2.12	3.26	6.01
I. mean	1.85	0.41	0.58	1.81	0.37	7.03	5.89	6.2	6.8	5.03	5.96	5.69	3.55	4.89	6.24
I. sorting	0.7	0.59	0.61	0.41	1.7	2.31	2.85	2.91	2.39	2.32	2.66	2.97	1.64	2.77	2.62
I. skewness 1	-0.23	-0.12	-0.09	-0.19	-0.03	-0.07	0.1	-0.12	-0.08	0.58	0.35	0.24	0.87	0.59	0.09
I. skewness 2	-0.9	-0.55	-0.73	0.17	0.27	-0.02	0.24	-0.07	-0.01	0.92	0.5	0.39	1.83	0.88	0.17
I. kurtosis	0.85	1.27	1.46	1.06	0.37	0.4	0.33	0.35	0.4	0.6	0.39	0.34	1.25	0.4	0.41
T. median	0.25	0.71	0.64	0.27	0.75	0.01	0.02	0.01	0.01	0.08	0.03	0.03	0.23	0.1	0.02
T. mean	0.27	0.74	0.62	0.29	1.33	0.01	0.04	0.03	0.02	0.07	0.04	0.06	0.22	0.1	0.03
T. sorting	1.32	1.29	1.22	1.16	2.77	3.13	4.46	4.3	3.34	2.4	4.09	4.78	1.3	3.92	3.99
T. skewness	1.08	1.01	0.89	1.13	1.29	1.25	0.79	1.48	1.36	0.46	0.39	0.49	0.85	0.23	0.87
T. kurtosis	0.13	0.17	0.09	0.19	0.42	0.22	0.26	0.19	0.23	0.3	0.3	0.28	0.19	0.35	0.26

SFBay-98 USGS grain size samples 43 - 56

Phi	-1	43	44	45	46	47	48	49	50	51	52	53	54	54R	55	56	56R
-1	0	0	2.82	16.25	23.06	0	0	0	0	0	17.46	14.42	0	0	2.06	4.86	7.22
-0.5	0	0	9.86	2.98	0	0	0	0	0	0	0.61	1.17	0	0	1.67	3.58	3.61
0	0	0	21.92	4.34	0	0	0	0	0	0	0.75	0.95	0	0	3.38	6.4	6.54
0.5	0	0	43.29	6.24	8.46	0	0	0	0	0	2.3	0.77	5.54	0.57	11.61	6.24	9.5
1	0.14	0.11	18.05	6.76	7.08	0	0.3	0	0	0	0.55	0.23	8.16	5.07	13.56	6.02	9.75
1.5	3.47	1.2	2.48	9.17	19.62	0	2.41	0	0	0	13.79	3.58	29.4	8.46	24.34	14.56	15.7
2	11.89	1.96	1.11	13.91	20.23	0.05	4.94	0.13	0.86	27.2	10.03	32.9	28.9	23.6	24.44	21.15	
2.5	14.5	5.48	0.33	14.83	9.23	1.52	9.55	0.75	3.24	19.89	13.19	16.6	32.4	13.1	23.42	18.67	
3	7.5	8.55	0.07	8.26	2.92	3.33	10.7	1.96	5.08	6.17	9.51	3.8	16.7	2.69	7.15	5.54	
3.5	4.6	8.7	0.07	3.21	1.15	5.2	8.6	5.91	9.12	1.7	6.34	0.7	4	0.46	0.77	0.58	
4	4.4	8.1	0	1.68	0.69	7.8	6.9	7.95	10.5	0.89	4.59	0.4	0.7	0.28	0.34	0.25	
4.5	4.2	7.1	0	1.15	0.54	8.9	5.7	8.1	9.3	0.65	3.76	0.2	0.3	0.28	0.17	0.08	
5	3.9	5.8	0	0.99	0.62	8.1	4.8	7.2	7.1	0.73	3.42	0.2	0.2	0.28	0.17	0.17	
5.5	3.4	4.8	0	0.99	0.62	6.5	3.8	5.9	5.2	0.73	2.92	0.2	0.3	0.28	0.26	0.08	
6	3.4	4.4	0	0.92	0.62	6	3.7	5.6	4.5	0.65	3	0.1	0.2	0.28	0.17	0.17	
6.5	3.7	4.6	0	0.92	0.62	5.8	3.8	5.7	4.5	0.65	2.75	0.2	0.2	0.37	0.17	0.08	
7	4.1	5	0	0.99	0.69	6	4.2	6.2	4.7	0.65	2.67	0.2	0.2	0.28	0.09	0.17	
7.5	4.6	5.7	0	1.07	0.62	6.2	4.8	7.2	5.4	0.73	2.84	0.3	0.3	0.28	0.26	0.08	
8	5.1	6	0	1.15	0.77	6.4	5.2	7.6	5.7	0.81	2.84	0.2	0.2	0.28	0.17	0.17	
8.5	4.9	5.7	0	0.99	0.69	6	4.9	7.3	5.4	0.73	2.59	0.2	0.3	0.19	0.17	0.17	
9	4.3	4.8	0	0.99	0.54	5.2	4.3	6.2	4.8	0.65	2.34	0.3	0.3	0.28	0.17	0.17	
9.5	3.6	3.8	0	0.76	0.46	4.8	3.5	5.1	4.2	0.57	1.92	0.2	0.2	0.19	0.17	0.08	
10	3.2	3.2	0	0.69	0.38	4.5	3.1	4.3	3.9	0.49	1.67	0.1	0.2	0.19	0.17	0.07	
10.5	2.7	2.7	0	0.46	0.23	4.1	2.6	3.7	3.5	0.32	1.34	0.08	0.2	0.07	0.07	0.01	
11	1.9	1.8	0	0.23	0.12	2.8	1.7	2.5	2.3	0.24	0.92	0.02	0.08	0.02	0.02	0	
14	0.5	0.5	0	0.08	0.03	0.8	0.5	0.7	0.7	0.08	0.25	0	0.02	0	0	0	
% Gravel	0	0	2.82	16.25	23.06	0	0	0	0	17.46	14.42	0	0	2.06	4.86	7.22	
% Sand	46.5	34.1	97.18	71.37	69.4	17.9	43.4	16.7	28.8	73.85	50.36	97.5	96.8	94.69	92.92	91.29	
% Silt	32.4	43.4	0	8.18	5.08	53.9	36	53.5	46.4	5.6	24.2	1.6	1.9	2.32	1.45	0.99	
% Clay	21.1	22.5	0	4.2	2.46	28.2	20.6	29.8	24.8	3.08	11.02	0.9	1.3	0.93	0.77	0.5	
% Mud	53.5	65.9	0	12.38	7.54	82.1	56.6	83.3	71.2	8.69	35.22	2.5	3.2	3.25	2.21	1.49	
Gravel/Sand	0	0	0.03	0.23	0.33	0	0	0	0	0.24	0.29	0	0	0.02	0.05	0.08	
Sand/Silt	1.44	0.79	0	8.73	13.67	0.33	1.21	0.31	0.62	13.18	2.08	60.94	50.95	40.77	64.18	92.08	
Silt/Clay	1.54	1.93	0	1.95	2.06	1.91	1.75	1.8	1.87	1.82	2.2	1.78	1.46	2.5	1.89	2	
Sand/Clay	2.2	1.52	n/a	16.98	28.19	0.63	2.11	0.56	1.16	23.94	4.57	108.33	74.46	101.93	121.24	184.16	
Sand/Mud	0.87	0.52	n/a	5.76	9.2	0.22	0.77	0.2	0.4	8.5	1.43	39	30.25	29.12	41.97	61.38	
Gravel/Mud	0	0	n/a	1.31	3.06	0	0	0	0	2.01	0.41	0	0	0.63	2.2	4.85	
1st moment	5.04	5.67	0.14	1.8	1.27	6.4	5.24	6.54	5.94	1.76	3.42	1.71	2.23	1.42	1.49	1.23	
Variance	8.45	6.54	0.32	6.29	4.65	5.52	7.39	5.19	6.16	4.81	9.97	1.2	1.33	1.81	1.95	1.8	
Std. deviation	2.91	2.56	0.57	2.51	2.16	2.35	2.72	2.28	2.48	2.19	3.16	1.09	1.15	1.35	1.4	1.34	
3rd moment	0.42	0.3	0.13	1.27	1.57	0.25	0.43	0.15	0.38	1.36	0.41	3.91	3.8	2.55	1.32	0.97	
4th moment	1.86	2.02	4.46	4.93	6.87	2.09	2.01	2.06	2.06	6.57	2.55	25.29	23.68	15.29	10.78	8.95	
F&W median	4.41	5.31	0.16	1.67	1.37	6.22	4.59	6.57	5.46	1.79	2.77	1.58	2.08	1.39	1.69	1.44	
F&W mean	4.98	5.61	0.15	1.26	0.8	6.41	5.17	6.52	5.9	1.09	3.2	1.57	2.08	1.33	1.36	1.18	
F&W sorting	2.9	2.59	0.53	2.41	1.98	2.41	2.74	2.32	2.51	2.11	3.46	0.57	0.59	0.85	1.09	1.16	
F&W skewness	0.3	0.18	-0.1	0.02	-0.12	0.11	0.3	0.01	0.25	-0.19	0.2	-0.04	-0.03	-0.13	-0.48	-0.35	
F&W kurtosis	0.65	0.73	1.18	1.55	1.69	0.78	0.71	0.75	0.75	3.06	1.16	1.33	1.32	1.04	1.15	1.02	
I. median	4.41	5.31	0.16	1.67	1.37	6.22	4.59	6.57	5.46	1.79	2.77	1.58	2.08	1.39	1.69	1.44	
I. mean	5.27	5.76	0.14	1.06	0.52	6.5	5.46	6.49	6.12	0.74	3.41	1.57	2.07	1.31	1.2	1.04	
I. sorting	3.25	2.82	0.53	2.09	1.67	2.6	3.01	2.53	2.72	1.78	3.71	0.49	0.51	0.84	1.11	1.12	
I. skewness 1	0.26	0.16	-0.04	-0.29	-0.51	0.11	0.29	-0.03	0.24	-0.59	0.17	-0.03	-0.02	-0.1	-0.45	-0.35	
I. skewness 2	0.43	0.29	-0.27	0.71	0.6	0.17	0.43	0.07	0.35	0.5	0.32	-0.14	-0.07	-0.28	-0.83	-0.6	
I. kurtosis	0.29	0.38	0.68	1.15	1.25	0.4	0.36	0.37	0.39	1.27	0.43	1.2	1.16	0.69	0.59	0.77	
T. median	0.05	0.03	0.9	0.31	0.39	0.01	0.04	0.01	0.02	0.29	0.15	0.33	0.24	0.38	0.31	0.37	
T. mean	0.1	0.05	0.92	0.55	0.61	0.03	0.07	0.02	0.04	0.34	0.16	0.33	0.23	0.43	0.4	0.5	
T. sorting	6.32	4.52	1.24	2.28	1.88	3.81	5.13	3.74	4.23	1.46	3.66	1.26	1.27	1.47	1.54	1.74	
T. skewness	0.47	0.65	1.01	1.63	1.73	0.86	0.42	1.23	0.54	1.2	0.3	0.91	0.92	1.12	1.38	1.38	
T. kurtosis	0.37	0.26	0.23	0.16	0.15	0.25	0.3	0.25	0.28	0.05	0.06	0.2	0.2	0.25	0.15	0.19	

Deep-Water Marine Benthic Habitat Classification Scheme

Key to Habitat Classification Code for Mapping and use with GIS programs

(modified after Greene et al., 1999)

Interpreted from remote sensing imagery for mapping purposes

Megahabitat – Use capital letters (based on depth and general physiographic boundaries; depth ranges approximate and specific to study area).

A = Aprons, continental rise, deep fans and bajadas (3000-5000 m)

B = Basin floors, Borderland types (floors at 1000-2500 m)

E = Estuary (0-300 m)

F = Flanks, continental slope, basin/island-atoll flanks (200-3000 m)

I = Inland seas, fiords (0-200 m)

P = Plains, abyssal (>5000 m)

R = Ridges, banks and seamounts (crests at 200-2500 m)

S = Shelf, continental and island shelves (0-200 m)

Seafloor Induration - Use lower-case letters (based on substrate hardness).

h = hard substrate, rock outcrop, relic beach rock or sediment pavement

m = mixed (hard & soft substrate)

s = soft substrate, sediment covered

Sediment types (for above indurations) - Use parentheses.

(b) = boulder

(c) = cobble

(g) = gravel

(h) = halimeda sediment, carbonate

(m) = mud, silt, clay

(p) = pebble

(s) = sand

Meso/Macrohabitat - Use lower-case letters (based on scale).

a = atoll

b = beach, relic

c = canyon

d = deformed, tilted and folded bedrock

e = exposure, bedrock

f = flats, floors

g = gully, channel

i = ice-formed feature or deposit, moraine, drop-stone depression

k = karst, solution pit, sink

l = landslide

m = mound, depression

n = enclosed waters, lagoon

o = overbank deposit (levee)

p = pinnacle (Note: Pinnacles are often difficult to distinguish from boulders. Therefore, these features may be used in conjunction [as (b)/p] to designate a meso/macrohabitat.

r = rill

s = scarp, cliff, fault or slump
 t = terrace
 w = sediment waves
 y = delta, fan
 z_# = zooxanthellae hosting structure, carbonate reef
 1 = barrier reef
 2 = fringing reef
 3 = head, bommie
 4 = patch reef

Modifier - Use lower-case subscript letters or underscore for GIS programs (textural and lithologic relationship).

a = anthropogenic (artificial reef/breakwall/shipwreck)
 b = bimodal (conglomeratic, mixed [includes gravel, cobbles and pebbles])
 c = consolidated sediment (includes claystone, mudstone, siltstone, sandstone, breccia, or conglomerate)
 d = differentially eroded
 f = fracture, joints-faulted
 g = granite
 h = hummocky, irregular relief
 i = interface, lithologic contact
 k = kelp
 l = limestone or carbonate
 m = massive sedimentary bedrock
 o = outwash
 p = pavement
 r = ripples
 s = scour (current or ice, direction noted)
 u = unconsolidated sediment
 v = volcanic rock

Seafloor Slope - Use category numbers. Typically calculated for survey area from x-y-z multibeam data.

1 Flat (0-1°)
 2 Sloping (1-30°)
 3 Steeply Sloping (30-60°)
 4 Vertical (60-90°)
 5 Overhang (> 90°)

Seafloor Complexity - Use category letters (in caps). Typically calculated for survey area from x-y-z multibeam slope data using neighborhood statistics and reported in standard deviation units.

A Very Low Complexity (-1 to 0)
 B Low Complexity (0 to 1)
 C Moderate Complexity (1 to 2)
 D High Complexity (2 to 3)

E Very High Complexity (3+)

Geologic Unit – When possible, the associated geologic unit is identified for each habitat type and follows the habitat designation in parentheses.

Examples: Shp_d1D(Q/R) - Continental shelf megahabitat; flat, highly complex hard seafloor with pinnacles differentially eroded. Geologic unit = Quaternary/Recent.

Fhd_d2C (Tmm) - Continental slope megahabitat; sloping hard seafloor of deformed (tilted, faulted, folded), differentially eroded bedrock exposure forming overhangs and caves. Geologic unit = Tertiary Miocene Monterey Formation.

Determined from video, still photos, or direct observation.

Macro/Microhabitat – Preceded by an asterik. Use parentheses for geologic attributes, brackets for biologic attributes. Based on observed small-scale seafloor features.

Geologic attributes (note percent grain sizes when possible)

- (b) = boulder
- (c) = cobble
- (d) = deformed, faulted, or folded
- (e) = exposure, bedrock (sedimentary, igneous, or metamorphic)
- (f) = fans
- (g) = gravel
- (h) = halimeda sediment, carbonate slates or mounds
- (i) = interface
- (j) = joints, cracks, and crevices
- (m) = mud, silt, or clay
- (p) = pebble
- (q) = coquina (shell hash)
- (r) = rubble
- (s) = sand
- (t) = terrace-like seafloor including sedimentary pavements
- (w) = wall, scarp, or cliff

Biologic attributes

- [a] = algae
- [b] = bryozoans
- [c] = corals
- [d] = detritus, drift algae
- [g] = gorgonians
- [n] = anemones
- [o] = other sessile organisms
- [s] = sponges

[t] = tracks, trails, or trace fossils

[u] = unusual organisms, or chemosynthetic communities

[w] = worm tubes

Seafloor Slope - Use category numbers. Estimated from video, still photos, or direct observation.

- 1 Flat (0-1°)
- 2 Sloping (1-30°)
- 3 Steeply Sloping (30-60°)
- 4 Vertical (60 - 90°)
- 5 Overhang (90°+)

Seafloor Complexity - Use category numbers. Estimated from video, still photos, or direct observation. Numbers represent seafloor rugosity values calculated as the ratio of surface area to linear area along a measured transect or patch.

- A Very Low Complexity (1 to 1.25)
- B Low Complexity (1.25 to 1.50)
- C Moderate Complexity (1.50 to 1.75)
- D High Complexity (1.75 to 2.00)
- E Very High Complexity (2+)

Examples: *(m)[w]1C - Flat or nearly flat mud (100%) bottom with worm tubes; moderate complexity.

*(s/c)1A - Sand bottom (>50%) with cobbles. Flat or nearly flat with very low complexity.

*(h)[c]1E - Coral reef on flat bottom with halimeda sediment. Very high complexity.

Shp_d1D(Q/R)*(m)[w]1C - *Large-scale habitat type*: Continental shelf megahabitat; flat, highly complex hard seafloor with pinnacles differentially eroded. Geologic unit = Quaternary/Recent. *Small-scale habitat type*: Flat or nearly flat mud (100%) bottom with worm tubes; moderate complexity.

Deep-Water Marine Benthic Habitat Classification Scheme

Explanation for Habitat Classification Code

(modified after Greene et al., 1999)

Habitat Classification Code

A habitat classification code, based on the deep-water habitat characterization scheme developed by Greene et al. (1999), was created to easily distinguish marine benthic habitats and to facilitate ease of use and queries within GIS (e.g., ArcView®, TNT Mips®, and ArcGIS®) and database (e.g., Microsoft Access® or Excel®) programs. The code is derived from several categories and can be subdivided based on the spatial scale of the data. The following categories apply directly to habitat interpretations determined from remote sensing imagery collected at the scale of 10s of kilometers to 1 meter: Megahabitat, Seafloor Induration, Meso/Macrohabitat, Modifier, Seafloor Slope, Seafloor Complexity, and Geologic Unit. Additional categories of Macro/Microhabitat, Seafloor Slope, and Seafloor Complexity apply to areas at the scale of 10 meters to centimeters and are determined from video, still photos, or direct observations. These two components can be used in conjunction to define a habitat across spatial scales or separately for comparisons between large and small-scale habitat types. Categories are explained in detail below. Not all categories may be required or possible given the study objectives, data availability, or data quality. In these cases the categories used may be selected to best accommodate the needs of the user. If an attribute characterization is probable but questionable, it is followed by a question-mark to infer a lower level of interpretive confidence.

Explanation of Attribute Categories and their Use

Determined from Remote Sensing Imagery (for creation of large-scale habitat maps)

1) Megahabitat – This category is based on depth and general physiographic boundaries and is used to distinguish regions and features on a scale of 10s of kilometers to kilometers. Depth ranges listed for category attributes in the key are given as generalized examples. This category is listed first in the code and denoted with a capital letter.

2) Seafloor Induration – Seafloor induration refers to substrate hardness and is depicted by the second letter (a lower-case letter) in the code. Designations of hard, mixed, and soft substrate

may be further subdivided into distinct sediment types, which are then listed immediately afterwards in parentheses either in alphabetical order or in order of relative abundance.

3) Meso/Macrohabitat – This distinction is related to the scale of the habitat and consists of seafloor features ranging from 1 kilometer to 1 meter in size. Meso/Macrohabitats are noted as the third letter (a lower-case letter) in the code. If necessary, several Meso/Macrohabitats can be included either alphabetically or in order of relative abundance and separated by a backslash.

4) Modifier – The fourth letter in the code, a modifier, is noted with a lower-case subscript letter or separated by an underline in some GIS programs (e.g., ArcView®). Modifiers describe the texture or lithology of the seafloor. If necessary, several modifiers can be included alphabetically or in order of relative abundance and separated by a backslash.

5) Seafloor Slope – The fifth category, represented by a number following the modifier subscript, denotes slope. Slope is typically calculated for a survey area from x-y-z multibeam data and category values can be modified based on characteristics of the study region.

6) Seafloor Complexity – Complexity is denoted by the sixth letter and listed in caps. Complexity is typically calculated from slope data using neighborhood statistics and reported in standard deviation units. As with slope, category values can be modified based on characteristics of the study region.

7) Geologic Unit – When possible, the geologic unit is determined and listed subsequent to the habitat classification code in parentheses.

Determined from video, still photos, or direct observation (for designation of small-scale habitat types)

8) Macro/Microhabitat – Macro/Microhabitats are noted by the eighth letter in the code (or first letter, if used separately) and preceded by an asterisk. This category is subdivided between geologic (surrounded by parentheses) and biologic (surrounded by brackets) attributes. Dynamic segmentation can be used to plot macroscale habitat patches on Mega/Mesoscale habitat interpretations (Nasby 2000).

9) Seafloor Slope – The ninth category (or second category, if used separately), listed by a number denotes slope. Unlike the previous slope designation (#5), the clarity of this estimate can be made at smaller scales and groundtruthed or compared with category #5. Category values can be modified based on characteristics of the study region.

10) Seafloor Complexity – The designations in this category, unlike those in category #6, are based on seafloor rugosity values calculated as the ratio of surface area to linear area along a measured transect or patch. Category letters are listed in caps and category values can be modified based on characteristics of the study region.

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Nasby, N.M. 2000. Integration of submersible transect data and high-resolution sonar imagery for a habitat-based groundfish assessment of Heceta Bank, Oregon. M.S. Thesis, College of Oceanic and Atmospheric Science, Oregon State University. pp. 49.

Comparison of remote sensing technologies (from Kenny et al. 2000)

Table 1. The three most commonly used AGDS systems to date.

<u>System</u>	<u>Remarks</u>
QTC – View	Analysis of first echo signals using PCA analysis.
RoxAnn	Uses the backscatter information from the first echo to characterise seabed roughness and reflection of second echo to characterise hardness.
EchoPlus	Dual frequency digital signal processing system using first and second echo analysis technique, including compensation for changes in frequency, pulse length and power levels. Unprocessed baseband signals are also obtained.

Note: AGDS = Ground discriminating single beam echo-sounders

Table 2. The footprint resolution *versus* range for two sidescan sonar systems.

Range (m)	Spacing between soundings (m) @ 4 knts	MS992 120kHz Sidescan 75° beam width	MS992 330kHz Sidescan 0.3° beam width
25	0.07	0.33	0.13
50	0.13	0.65	0.26
100	0.26	1.30	0.52
200	0.52	2.60	1.00
500	1.30	6.50	n/a

Table 3. The relative performance of different sidescan sonar systems.

Sonar Frequency kHz	Type	Horizontal Beam (degrees)	Typical range under average conditions		Total swath width (m)	Typical survey speed (knots)	Typical coverage (km ² .h ⁻¹)	Resolution or 'detectability' under optimal survey conditions					
			Seconds	Metres				Cable 100 m	Wreck 50 m	Container 10 m	Oil drum 2 m	Mine 1 m	Bottle 0.1 m
500 (380)	c.w.	0.2	0.1	75	150	3	0.8	●	●	●	●	●	●
100	c.w.	1.0	0.25	187	375	5	3.5	●	●	●	●	●	○
50	c.w.	1.5	0.5	375	750	6	8.3	●	●	●	○	○	○
200	f.m. chirp	0.5	1	750	1500	4.5	12.5	●	●	●	●	●	○

Table 4. The relative performance of two multibeam echosounder systems.

Water depth	Spacing between soundings @ 12 kts	EM1000 3.3° beam width			EM3000 1.5° beam width		
		Footprint (m) nadir	Footprint (m) 30°	Footprint (m) 75°	Footprint (m) nadir	Footprint (m) 30°	Footprint (m) 75°
Metres	Metres						
50	1.6	2.9	3.3	12.0	1.3	1.5	5.0
100	3.2	5.8	6.6	24.0	2.6	3.0	10.0
200	6.4	11.6	13.2	48.0	5.2	6.0	n/a
500	16	29	33	n/a	n/a	n/a	n/a
1000	32	58	66	n/a	n/a	n/a	n/a

Table 5. The area of seafloor mapped by sidescan sonar and MBES in a given time under varying operational conditions.

Water depth (m)	EM1000 multibeam @ 12 kts			MS992 330 kHz Sidescan @ 4 kts		
	Horizontal width (m)	Maximum footprint (m)	Coverage (km ² per day)	Horizontal width (m)	Maximum Footprint (m)	Coverage (km ² per day)
10	70	2.4	40	400	1.0	67
50	350	12	195	400	1.0	67
100	700	24	390	400	1.0	67
200	1400	48	780	400	1.0	67

Note: MBES = Multibeam echosounder

Table 6. Area of seafloor mapped (expressed as unit effort, $\text{km}^2 \cdot \text{h}^{-1}$) versus resolution for different remote sensing systems.

System	Area Mapped	Resolution (horizontal)								Remarks
	$\text{km}^2 \cdot \text{h}^{-1}$	1000 m	100 m	10 m	1 m	1/10 m	1/100 m	1/1000 m	< 1/1000 m	
Remote Sensing, Satellite (SAR)	>100	●	●	●						Restricted to operational coverage and mainly shallow seas
Remote Sensing, Aircraft (CAST)	>10	●	●	●	●					Generally restricted to water depths < 6 m
'Chirp' Side Scan Sonar	10		●	●	●					High energy broad bandwidth pulse sonar
Multi Beam Bathymetry	5		●	●	●	●				Allows the use of backscatter data to characterize substrata
Side Scan Sonar	3.5		●	●	●	●	●			Size of surface coverage (swath) depends on the frequency used
Synthetic Aperture Sonar	3.0					●	●	●		Optimal operation at 50 - 100 kHz
Single Beam (AGDS)	1.5		●	●	●	●				Nominal (narrow) beam surface coverage
High Resolution Sub-bottom Profiler	0.8	●	●	●	●	●				Narrow beam sub-surface coverage
Video Camera	0.2				●	●	●			Allows mega-epibenthos identification and provides ground truth for acoustic survey mapping technology.
Benthic Grab/Core Sampling	0.003					●	●	●		Quantitative data on the macro and meiofauna requires additional analysis in a laboratory
Sediment Profile Camera	<0.001						●	●		sediment/water interface inspections
X-ray photography	<0.001						●	●	●	High resolution geochemical and physical inspections (water content, density)

The relationship between the sediment, its stability and relevant processes of physical disturbance is given in Table 7. All these processes may have an impact on the ecology of the benthic fauna and flora. Table 7 also indicates which technique is best suited for identifying each of the conditions described.

Table 7. The relationship between 'rapid' continental shelf seabed processes, seabed substrata and marine mapping systems for habitat discrimination

		Seabed Environmental Conditions																							
		outcropping bedrock				gravel				clean sand (non-cohesive <8-10% mud)				cohesive sediments				Bioherms (shells, maerl, mussel-beds)							
		Tidal	Wave	Other ⁵	Storm	Tidal	Wave	Other	Storm	Tidal	Wave	Other	Storm	Tidal	Wave	Other	Storm	Tidal	Wave		Other	Storm			
Physical Seabed Processes	Bedform migration, (sand waves, gravel lineations, wide-scale sediment transport)	○	○	○	○	●	Shallow water only	●	●	●	●	●	●	○	○	○	○	●	●	●	●	Repeated surveys with sidescan sonar, multibeam & time-lapse photography			
	Scour, (localised sediment transport)	○	○	○	○	●	Shallow water only	●	●	●	●	●	●	○	○	○	●	●	●	●	Sidescan sonar, multibeam & time-lapse photography				
	Liquefaction (wave loading)	○	○	○	○	○	○	○	○	○	Shallow water only	Shallow water only	●	○	○	○	○	○	Shallow water only	Shallow water only	●	Lab measurements and field investigations using density penetrometers			
	Subsidence (substrata sinking under its own weight)	○	○	○	○	○	○	○	○	○	○	○	○	●				○	○	○	○	Sidescan sonar, multibeam and very high resolution seismic reflection profiling			
	Sedimentation (rapid events)	○	○	○	○	○	○	○	○	○	○	○	storm deposits	○	○	○	○	●	○	○	○	○	Very high resolution seismic reflection profiling, core inspection and sediment profiling camera		
	Anthropogenic activities (trawling, dredging)	minimal physical effects				moderate to severe physical effects				moderate physical effect				potentially severe physical effects				potentially severe physical effects				Sidescan sonar and multibeam			
	Gas venting	habitat enhancer				habitat enhancer				habitat enhancer seabed stabilizer				habitat enhancer erodes + stabilizes				product of				Sidescan sonar, multibeam and very high resolution seismic reflection profiling			
Nearbed density flows on the shelf	○	○	○	○	○	○	○	○	○	○	○	○	●	○	●	●	○	○	○	○	Multi-frequency echosounders				
Slope failure (land slip)	○	○	○	○	○	○	○	●	○	○	○	●	○	○	○	●	○	○	○	●	Sidescan sonar, multibeam and very high resolution seismic reflection profiling				

● Denotes that a process may occur under the specified environmental conditions (defined as a combination of the substrata and hydrodynamics), and that the process feature is best detected by the prescribed mapping system.

⁵ Other periodic currents such as upwelling and surges.

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